

A Guide to the Manufacture, Performance, and Potential of Plastics in Agriculture

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A Guide to the Manufacture, Performance, and Potential of Plastics in Agriculture

Edited by

Michael D. Orzolek



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Dedication

To my wife Judy, the love of my life and inspiration for the last 48 years.

—Michael D. Orzolek

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Biography of the Editor

Michael D. Orzolek is Professor Emeritus of Vegetable Crops, Department of Plant Science, The Pennsylvania State University. Since 1981, he had a three-way appointment—60% extension, 22% research and 18% teaching. Since his retirement in June 2012, he has kept active conducting applied field research and moving his office to the Horticulture Research Farm, Rock Springs, PA. He has done extensive research on stand establishment, plastic mulches, high tunnels, weed management, and tillage systems. Mike is still the current director of the Penn State Center for Plasticulture and the CP High Tunnel Research and Education Facility at Rock Springs, PA.

Dr. Orzolek formerly was Extension Vegetable Specialist at the University of Delaware (1974–81). He received his B.S. in biology from Alliance College, his M.S. in horticulture from West Virginia University, and his Ph.D. in horticulture/botany from the University of Maryland.

1 Introduction

Michael D. Orzolek

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History—North America

Plasticulture is not, of course, plastic cultivation, though some crops produce natural plastics (caoutchouc from *Hevea* or guayule). Plasticulture takes care of plastic materials' use in agriculture, not including applications that are not concretely agricultural activities (building insulation, fresh goods packing, etc.). They can be old techniques (mulching or drainage) that plastics have expanded notoriously or completely new techniques (localized irrigation or floating row cover), economically viable only with plastic materials. In the 1980s, plasticulture involved more than 2 million tons per year plastic consumption in the world. A great number of polymers were used, from the expanded polystyrene of seedling trays to the polypropylene (PP) strings for plant knitting.

The use of plastics in agriculture in the United States (polyethylene (PE) or PP resin) was first evaluated on greenhouses that produced vegetables for commercial sale. Dr. Emery Emmert was the first land-grant scientist at the University of Kentucky to evaluate plastic film that covered his greenhouse in 1960. Interest in this new technology led to the formation of the National Agricultural Plastics Association (NAPA) that was later changed to the American Society for Plasticulture (ASP) to include all the facets of plastic use in agriculture. These two professional organizations included university personnel, manufacturers in the production of plastics, government personnel, and students. The first meeting of NAPA was held in 1960 at Lexington, Kentucky, USA, to discuss the needs and challenges of using plastics to improve agriculture. Since that first meeting in Lexington, annual NAPA and later ASP meetings were held in various regions of the United States to discuss new technologies, innovative/creative uses of existing technology and products that enabled growers to maximize the production of their agricultural crops.

Several notable Extension Educators were leaders in the promotion of plasticulture for horticultural crop production in the late 1960s and 1970s in the United States. Norman J. Smith, Rutgers University Extension Educator, traveled extensively to study, apply, and promote the use of plastic mulch and drip irrigation throughout the United States and many other countries in the world. Norman received a BS in Vegetable Production from Cornell University in 1949 and a MS in Vegetable Production and Entomology from Michigan State University in 1959. Bernarr J. Hall, University of California Riverside Extension Educator, introduced plastic tunnels, row covers, and drip irrigation to Southern California growers on a large scale. Bernarr was also heavily involved with NAPA and the International Society for Plastics in Agriculture being president of both societies during his professional career.

The first large-scale use of PE film worldwide was in the construction of plastic-covered greenhouses. The first plastic-covered greenhouse was erected in 1955 in England. In the late 1960s and early 1970s, construction of plastic-covered greenhouses was found in Russia, southern Europe, and Asia (notably Japan). Meanwhile, Israel had extensive areas of high-value horticultural crops under plastic tunnels, row covers, and plastic soil mulches by 1971, paralleling the development and use of drip or trickle irrigation to maximize crop production. China began using plastic film covers to protect rice seedbeds from the adversities of cold, windy spring weather in the central and southern provinces in 1958. There was widespread use in both China and Japan by 1965, and rapid expansion through the 1970s in China, Japan, and Korea. By 1980, there were 8600 ha of plastic greenhouses in Japan and, by 1984, 16,000 ha in China. In the early 1970s, the Mediterranean and Middle Eastern countries of Spain, Italy, Greece, Algeria, Portugal, Turkey, Jordan, and those countries bordering the Arabian Gulf became prominent in the construction of plastic greenhouses and in the production and marketing of high-value greenhouse-grown crops. It was not until 1980, however, that the first plastic greenhouses were constructed in Egypt, following a research project financed by the World Bank. The use of plastic greenhouses for horticultural crop production in Australia, New Zealand, Chile, Argentina, and South Africa paralleled those in the United States. The use of plastic for covering greenhouses in these countries was an attempt to produce fruits and vegetables 12 months of the year under extreme environmental conditions. Also, many countries had minimum cultivated land available for the production of agronomic and horticultural crops as well as animals that were important for their Mediterranean diets.

After the oil crisis in 1973, the European crop diversification programs expanded the plasticulture uses for crop production. Population increase and better life standards spread into the cultivated areas and the production of fresh vegetables (out of the conventional cropping seasons), expanding the use of plastic for crop production. Water scarcity developed the use of reservoirs. New techniques, like soilless culture, increased plastics uses. The enlargement of agricultural plastic types (thermal films, linear low-density polyethylene (L-LDPE), etc.) allowed new and improved applications.

The differences in climate between the European countries determined the relevance of the various crops in each country and, consequently, the importance of each plasticulture technique. Ensilage (chopped corn), a generalized technique in Northern Europe, was not so frequent in southern areas, where forage crops were not grown on large acreage. On the other hand, the higher radiation and mild winter temperatures of southern areas, especially near the sea, generated better ecological conditions for growing horticultural crops that were suited for the use of thermoplastic products.

All uses of plastic materials for agricultural production in the 1980s was about 550,000 tons per year in France, Italy, and Spain, without including plastic materials for packaging of agricultural products. The most common plastic material was low-density polyethylene (LDPE), which in Spain reached around 60% of total plasticulture use, followed by high-density polyethylene (HDPE), PP, polyvinylchloride (PVC), polyester, and ethylene-vinyl-acetate copolymer (EVA). Plastic films were around 65% of total thermoplastic compounds used in the Spanish agricultural sector, while tubes reached 25%. Plastic material consumption for agriculture in Spain reached 9% of total national consumption in the 1980s, fourth place after the packaging, building, and electricity industries.

The largest use of PE resin was in the development of plastic film mulch that was placed on top of the soil surface to increase soil temperature, to maintain higher levels of soil moisture, and to reduce/eliminate weeds. Today, millions of pounds of plastic mulch are used extensively around the world including China that has to feed 1.2 billion people every day. Considering that LDPE was not discovered until 1935 and HDPE and propylene were not discovered until 1951, the worldwide use of these materials has reached staggering numbers by agricultural users to feed the growing world population.

Film Manufacturing

In the early 1960s to the late 1990s, there were several dozen PE film manufacturers of plastic mulch, covers, and silage bags in the United States. Because of the fluctuating prices of raw resin and competition from overseas, there are currently less than eight agricultural film manufacturers in North America. In addition, the number of agricultural crop growers in the United States has dropped by 15%, many of whom were users of plastic mulch film and drip irrigation tape. While there has been development of many new uses of PE film for consumer use, such as covering for styrofoam trays used in the packaging industry, there has not been a significant change in the manufacturing of the plastic film. Film is either blown or cast. Blown film is one of two principle processes used to fabricate film products. Films are typically defined as less than 0.254 mm (10 mil) in thickness, although blown film can be produced as high as 0.5 mm (20 mil). The blown film process is used to produce a wide variety of products, ranging from simple monolayer films for bags to very complex multilayer structures used in food packaging.

The cast film process involves the extrusion of polymers melted through a slot or flat-die to form a thin, molten sheet or film. This film is “pinned” to the surface of a chill roll (typically water-cooled and chrome-plated) by a blast of air from an air knife or vacuum box. The film quenches immediately and then has its edges slit prior to winding. Because of the fast quench capabilities, a cast film generally has much better optics than a blown film and can be produced at higher line speeds. However, it has the disadvantage of higher scrap due to edge-trim and very little film orientation in the cross-direction.

Additives

Since PE films are subject to photo/thermal oxidation characterized by a steady decline in physical properties of the film, additives are incorporated into the PE resin before being blown or cast into plastic mulch. Stabilizing chemicals are added to the resin which contributes in maintaining the mechanical and optical properties of the film during its lifetime, even under severe environmental conditions. In addition

to the light stabilizing chemistry incorporated into the PE resin, chemicals are used to reduce condensation on the inside of the film as well as to reduce the dirt from building up a layer on the film. The newer film technology incorporates chemistry into the PE resin that will both reduce the buildup of heat inside a greenhouse or high tunnel and maintain higher nighttime temperature inside the greenhouse or high tunnel by decreasing reradiation of the solar energy captured during the daylight hours.

Plastic Mulch

The use of plastic film mulch by horticultural crop growers around the world has steadily increased over the past 30 years because of the many advantages of using plastic mulch to grow horticultural crops. Plastic mulch will warm the soil in spring in cool climates by an average of 8–10°F depending on ambient air temperature, sunlight, soil type, available soil moisture, and mulch color. Plastic mulch (especially black) will help reduce/eliminate weed growth under the plastic film through light exclusion. Plastic mulch will maintain a higher soil moisture level by reducing/eliminating evaporation from the soil surface. Higher levels of plant nutrients are maintained under the plastic film in the bed because of reduced leaching especially with high rainfall events. In semitropical and tropical climates, white-on-black plastic mulch can reduce soil temperature by an average of 6–8°F. Initially, all plastic film mulch had been black. Some manufacturers produced clear film mulch to increase soil temperature 8–10°F higher than black film. While clear plastic mulch did in fact raise soil temperatures higher than black, it also allowed significant weed growth and competition beneath the plastic mulch that eventually was pushed up by the weeds. As scientists realized that there was a pigment in plants (phytochrome) that was able to distinguish between red and blue wavelengths of light, various film manufacturers began producing different colors of plastic mulch. A range of colored plastic mulch film became available from different manufacturers for specific crop applications. The colors included red, blue, infrared thermal green, brown, silver, and white. There were also specialty plastic film mulches developed such as a 12 in. black strip in the middle of a 48 in. wide white, metalized silver or clear film.

Row Covers

Row covers were developed to minimize low temperature damage to warm season vegetable crops such as tomato, pepper, and eggplant in locations where temperatures below 40°F were experienced in late spring and early fall. In addition, row covers exclude insect pests by acting as a physical barrier. Typically row covers are PP fabric that are somewhat porous and are manufactured in very large sheets as large as 50,000 ft². Row covers also reduce the evapotranspiration rate in field vegetables and help to maintain higher soil moisture levels compared to no row cover. Wind blowing across a field of vegetables will result in desiccation of vegetable transplants in the field over time because of water loss. Row covers reduce wind stress and desiccation and consequently enhance plant growth and development. Since row covers enhance temperature and soil moisture under the covers, weeds can grow as vigorously as the planted crop unless controlled by a preemergent or postemergent herbicide application. Row covers can be applied over individual crop rows with the use of metal hoops or large sheets of row cover can be placed on top the crop over a large area (50,000 ft²) in which case it is called a floating row cover.

Drip Irrigation

The introduction of drip irrigation tape changed the face of modern agriculture because it increased irrigation efficiency by 90–95% with direct water delivery next to the root system of cultivated crops. Many growers also have incorporated fertilizer injection into the drip system with more efficient use of fertilizers since the nutrients come directly in contact with root hairs and plants respond to more efficient nutrient utilization. In addition, plant diseases are reduced since the foliage does not get wet with irrigation water. Drip irrigation tape is available in different orifice spacing, different water flow rates, and different tape thickness. Depending on the water source (rivers, ponds, lakes versus well), most drip irrigation systems require a filtration system. The one disadvantage of using drip irrigation tape is that it is an annual input and has to be taken out of the field and disposed when crop production is complete every year. New drip tape is used on an annual basis because during the course of the growing season, insects,

rodents, and birds damage the drip tape in search of water, especially in hot, dry years.

High/Low Tunnels

High tunnels were constructed in Europe about the same time that Dr. Emery Emmert, University of Kentucky, Lexington, USA, constructed his first greenhouse/high tunnel out of wood and PE film. However, the Chinese were growing vegetables in crude high tunnels in the late 1930s and early 1940s. The reason why high tunnels had become so popular with growers compared to greenhouses of comparable square footage was their inexpensive cost to buy or construct a high tunnel. Greenhouses compared to high tunnels of the same growing surface area are approximately 10–15 times more expensive depending on the degree of automation. High tunnels are heated by the sun through solar energy and vented by rolling up one or both sides of the high tunnel. Greenhouses have heaters with automated fans and louvers for controlling temperature for specific crop production as well as computerized watering and fertilizing systems.

Plastic Greenhouses

In the late 1960s and early 1970s, almost all small greenhouse structures (less than 5000 ft²) were covered with a double layer of 6 mil PE film inflated with a fan to not only enhance the insulation properties of the plastic film but also eliminate billowing and stress on the plastic film during high wind events. Generally, the plastic film would last 4–6 years depending on high wind events and number of sunny days the film was exposed to during the year. Plastic greenhouse can be found in many countries besides the United States, including Japan, China, Spain, Italy, Korea, Turkey, Morocco, Columbia, Portugal, Poland, Jordan, Saudi Arabia, Costa Rico, and Egypt. Growers in these countries are growing various horticultural crops in the plastic greenhouses because the structure protects the crops from excessive rains and high or continual winds as well as from intense sunlight and heat.

Rigid Molded Plastics

Rigid molded plastics, such as plastic flats, 1–10 gal plastic pots, plastic labels for plant identification, hoppers for fertilizer spreaders used in landscape applications, and so forth have been used by the bedding plant, floriculture, and landscape industries for the past 30 years. Many of the rigid plastic products are not recycled for crop production and are used only once before being placed in recycling or trash collections. Rigid plastic products are available in varied thickness, colors, and shapes for a specific industry or use. Several manufacturers even make storage sheds and water storage tanks out of PE resin because the rigid shed or water storage tank are somewhat portable, easy to maintain, and cheaper than a comparable wooden storage container.

Plastics in Animal Production

Disposal of Plastics

When PE film was introduced to agriculture in the 1960s, there was no specific plan developed by industry or users to deal with the used agricultural plastics because of the small volume of PE film used by growers. As more growers adopted plastics in agriculture and more volumes of PE film were manufactured for agricultural use, there still was no master plan to deal with disposal of agricultural films. In the 1970s and 1980s, growers were either stockpiling the used agricultural plastics in a corner of their farm not visible to the general public or it was burned in the field. Research conducted in the Pennsylvania State University demonstrated that PE and PP plastic film products could be burned in a specially designed burner at 2000°F with very little ash deposits. Stack tests were also conducted to measure emissions from the combusted plastic film and it turned out that plastic film products burn cleaner with minimum harmful emissions to humans and the environment compared to coal.

Plasticulture in Europe: History

By Dr. Nicolas Castilla, Agricultural Research and Training Institute, Andalucia, Spain.

Protected Cultivation: Early History

The first documented attempts at protected cultivation date back to Imperial Rome, where small mobile structures were used to grow cucumber plants, which were taken outdoors when the weather was favorable or kept covered otherwise. Mica and alabaster sheets were used as the covering material. In the 19th century, the first greenhouses with a gabled cover were constructed, which then expanded from Europe to America and Asia, being located near large cities. In the 20th century, economic development, especially after World War II, spurred the building of glass greenhouses in both Europe and the United States. But the appearance of plastics enabled the enormous expansion of the surface area of greenhouses in the Orient (mainly China and Japan) and in European Mediterranean countries (especially Italy and Spain).

A screen (fabric) or protective shelter placed over or next to the plant changes the environmental parameters that affect the whole plant or part of it, altering the energy balance of the plant and its environment. The position of the screen/fabric with respect to the plant determines the type of protection provided by the polymer material. Windbreaks, constitute vertical plant protection from wind and desiccation. When the screen is situated over the soil, below the above-ground parts of the plant, the result is mulch. When the screen is placed over the plant, it is a third type of protection: floating covers, tunnels, and greenhouses.

In Spain, the increase in the level of protection for vegetable growing began with very simple windbreaks in the early 1900s in the Southeastern areas, complemented later by the use of sand mulch and followed in the 1960s by the introduction of the flat-roofed *parral*-type greenhouse, an adaptation of the wire and wood structure locally used to support vines for growing table grapes (similar to the Italian *pergolato*). This greenhouse structure of low height fixes and supports the plastic film between two grids of wire. The roof geometry developed later for easier shedding of the infrequent rain and for improving solar radiation transmission and raising the roof height.

Mulches

In soil mulching, all the traditional materials were practically replaced by plastic materials due to the ease of handling, availability, and standardization that these materials allow. The plastic initially

used was LDPE evolving to (L-LDPE type of thin gauge (to reduce costs). The most common types used were black in color (to control weeds) or clear (to increase soil temperatures and achieve early harvests in crops). One special use of these latter types is the solarization of the soils, which is an environmental-friendly method of physical disinfection. White plastic mulches have been used to reflect radiation and reduce soil temperature. In addition, the reflected radiation can limit the presence of some insect species, and therefore materials specifically designed for this purpose have been developed, these having strong reflective power, such as aluminized or metallized-coated plastics. Mulching was adopted worldwide with more than 2 million hectares in the 1980s, over 80,000 ha in France and 50,000 ha in Spain.

Film thickness lowered from initial values of 50 μm to around 15 μm , as a result of the introduction of L-LDPE and better film-manufacturing. Photodegradable mulch films, initially developed in France, were not widely adopted because variable radiation conditions can induce an early degradation in high sun radiation areas or limit the degrading process in low radiation areas. Biodegradable films that are stable in contact with the air and degradable in contact with the soil through microbial activity are becoming a more viable option for many growers because of the agricultural plastic disposal problem.

Low Tunnels

In the 1980s, more than 25% of low tunnels in the world (200,000 ha) were located in Europe, basically in the South. Films used to cover the low tunnels were of high transmission in the photosynthetic-active radiation (PAR) range. They evolved from the conventional LDPE to the thermal types (EVA and infrared LDPE) with scarce use of PVC films. The initial thickness of 75 μm decreased to 25 μm .

Floating Row Covers

Floating row covers (also known as direct covers and floating mulches) consist of covering the crop with a flexible perforated sheet of plastic or a permeable spunbonded nonwoven fabric of very low weight (agrotextile). The low application cost of direct cover accelerated its

relevant spread as a substitute for low tunnels. In the 1980s the area was around 25,000 ha.

The materials were normally reused for more than one crop cycle, with a predominance of spunbonded PP providing a complementary protection against insect damage, due to the absence of holes as compared to perforated LDPE films used for row covers.

Agrotextiles are nonwoven materials comprising fine filaments (20–25 μm in thickness), heat soldered to form a netting. They are manufactured mainly with PP, polyester, and polyamide filaments; agrotextiles are air and water permeable and have agronomic characteristics similar to those of PE films.

LDPE films are around 0.05 mm thick, perforated to allow air exchange within the low tunnel and are generally placed over metal hoops spaced 2 m apart in the row. Usually, the film has 500 perforations/ m^2 of approximately 1 cm in diameter. In cold zones, the number of perforations decreases, while in areas of strong winds the number increases to reduce flapping of the plastic, which could deteriorate the plastic and damage the crop. Sometimes, plastics with thermal additives are used, such as EVA.

Greenhouses

The energy crisis and the introduction of plastic film were major contributing factors to the shift in European greenhouse vegetable production to the Mediterranean region where the low-cost, plastic greenhouses, and the development of simple technologies enabled the production of low-cost, out-of-season commodities in a region where the climatic advantages are related to the high-radiation conditions in the autumn and winter, the mild winter temperatures, and the climatic stability influenced by the vicinity of the sea.

The Mediterranean basin (including all the countries of Africa, Asia, and Europe limiting the Mediterranean Sea, located between 30°N and 46°N latitudes approximately) is the leading area in protected cultivation with over 65,000 ha of greenhouses and high tunnels in 1987. In 1999, there were 144,000 ha of greenhouses and high tunnels. On the contrary, the greenhouse area in the countries of the European Union (excluding the Mediterranean) was around 20,500 ha, with small variations in the past decades.

The percentage of plastic-covered greenhouses (high tunnels are included within greenhouses) exceeded 95% in all the Mediterranean

European Union countries (reaching 99% in Spain, 98% in Portugal, 95% in Greece, and 91% in Italy), while, in the Northern European Union countries, plastic-covered greenhouses were very low (2% in the Netherlands and Denmark, 5% in Belgium, 10% in Germany), with glasshouses predominant. This generalized rise of the plastic greenhouse industry has been mostly based on the use of low-cost structures.

The “Mediterranean greenhouse agrosystem” is characterized by the low technological and energy inputs. The use of simple structures, a generally low level of technology, and the lack of equipment for climate control, which are typical characteristics of Mediterranean greenhouses, creates a very strong dependence of the greenhouse microclimate on external conditions. This agrosystem has been evolving from very simple locally made wooden structures, without climate control other than natural ventilation, to more complex industrial-type greenhouses, typically the multispans arched-roof structure with a wide range of equipment, but the fact is that plastic-clad simple greenhouses clearly predominate over the more complex ones in the Southern European countries.

The globalization of the markets has increased the competitiveness of many edible crops in the past decade, highlighting the need for increased quality of the greenhouse produce, through better climate control. An economic compromise between the higher investment costs of better-equipped greenhouses and their agricultural performances is needed, in order to produce commodities of good quality at competitive levels.

Greenhouse Area

Plastic greenhouse expansion had been enormous during the 1980s, with a total of more than 150,000 ha in the world. Around 40% were located in Europe. The use of semirigid plastic materials was scarce, normally limited to sophisticated greenhouses (polycarbonate (PC), polymethacrylate (PMMA), PVC, and polyester). In plastic films, LDPE was leading polymer.

The evolution of the protected area in Spain (23,850 ha in 1989 and 47,700 ha in 1999) shows stabilization at the beginning of the 21st century. Recent estimates of the Spanish greenhouse area, including walk-in tunnels, reached slightly over 53,800 ha. These figures do not include fruit tree net-shelters (over 6500 ha) which are mainly used for hail protection of table grapes, loquat, and citrus trees in the Southeast of Spain.

Until 1950, the only material used for greenhouse covers was glass and is still being used in Holland, Germany, United Kingdom, Belgium, and Denmark. Plastics, due to their lower cost and the possibility of using lighter and thus more economic structures, became dominant as the cover material. The flexible plastic film most frequently used is LDPE, the cost of which is clearly advantageous (compared to rigid materials), despite the need to change the material periodically.

Covering Materials

Rigid Types

Within the category of rigid plastic panels, the most commonly used are PC, methyl PMMA, polyester reinforced with fiberglass, and PVC. PC is mostly used in cellular or multialveolar panels (a double-layer structure with an air gap in the interior), 4–16 mm thick. Although transmission is less than that of glass, the weight of the material is up to 10 times lower and its thermal properties are similar.

PMMA can be obtained as a simple corrugated sheet (in 1–3 mm thickness) or with an alveolar structure that can reach up to 32 mm in thickness. The reinforced fiberglass has an average service life of about 10 years. Due to its high cost, efforts have been made to increase its lifespan by the addition of other polymers such as vinyl polyfluoride, ethylene terephthalate, or acrylic gels, or by the protection of an exterior film. The most usual form of product specification is the undulated sheet.

Plaques of bi-oriented PVC have good mechanical resistance with low thickness (0.8–1.0 mm), lasting around 10 years. The main type is an undulated plate, although it can be found in plane plates and less frequently alveolated.

Flexible Types

The most widely used group of materials is derived from LDPE, which easily allow additives for better optical and thermal properties as well as durability. Long-life PE made of resins with low-fluidity indices and high degrees of polymerization have stabilizers as additives against the action of ultraviolet (UV) rays. In this technique of improving the thermal profile of plastic, the copolymerization of ethylene is normally used with EVA. The usual copolymerization ratio varies from 6% to 18% of EVA.

The wide assortment of plastic films offered to growers is based on the possibility of improving radiation transmission both quantitatively and qualitatively. Increased use of long life (UV) and thermal PE films instead of the conventional PE film is a first step.

The possibility of coextruding various layers of plastic at once produces multilayer films. The most usual are normally the three-layer films, in which materials are combined in such a way that the film has good mechanical resistance and light (PAR) transmission, has an antultraviolet effect on the outside, and has an anticondensation effect on the inside, plus thermal properties and, in many cases, high diffusive power (conversion of direct solar radiation into diffuse radiation).

The photosensitive plastic films that alter the ratio “red/far red” of incoming light, affect plant morphogenesis, or reduce crop diseases (*Botrytis*), or modify the behavior of insects (influencing their vision) by blocking certain wavebands of the solar radiation spectrum (UV blocking) or limiting the sun energy load (NIR, near infrared, blocking) are now commercial.

Nowadays, there is a general trend to use covering materials which diffuse the incoming light, without relevant reduction of transmission values, thereby contributing to improve crop production and radiation use efficiency.

Screenhouses

Another group of materials for covering greenhouses involves nets or screens. Although in some cases its use is to reduce solar radiation (e.g., protect plants with shade or to acclimatize crops), in most cases the aim is to control excess temperature. The high air permeability of screens (according to the number of threads per centimeter) lessens the wind load and therefore the structure of screenhouses can be light and economical. The screenings are widely used to create shade or cool greenhouses and are useful in low-rainfall areas and during periods of the year in which minimum temperatures are not very low.

Covering crops with flexible porous screens (nets) is becoming a common practice. “Screenhouses” are effective and economical structures for shading crops, protecting them from wind and hail, improving the temperature and humidity regimes, saving irrigation water, and excluding insects and birds. In the south of Spain, the lack of greenhouse production in coastal areas during the high air temperatures of the summer months is being replaced with vegetable produce

from screenhouses in the highlands, enabling year-round supply to the market.

Irrigation and Drainage

Plastic pipes for irrigation and drainage purposes replaced conventional material pipes in most cases. The availability of low diameter plastic pipes made the localized irrigation technique, mainly drip irrigation, economically feasible.

LDPE was used in low diameter pipes, while PVC was the leading polymer in big size irrigation pipes (over 25,000 tons per year in Italy) and in drainage pipes (over 35,000 tons per year in France), at that time (1980s).

Excluding some short-life PE dripping pipes, which were only used for one crop, all the other applications were long-lasting (up to 10 or more years), even being exposed to the ultraviolet sun rays.

Ensilage

The use of black LDPE films in the ensilage of forage crops was an extended technique in Europe, especially in northern areas where these crops are common. The film thickness was lowered from initial values of 200–130 μm .

Forage bale wrapping in the field with retractile PE increased, while conventional ensilage was partially replaced by bag ensilage.

Other Applications

As in other production sectors, plastic uses in agriculture reached important tonnages in the 1980s: PP strings (20,000 tons per year in Italy), cropping containers (10,000 HDPE tons per year in Italy), windbreaks (3200 ha in Spain), plant pots (6000 PP tons per year in Italy), cropping meshes, seedling trays, and nursery bags.

Outstanding increases were expected in thermoplastic products for soilless culture, where white PE film consumption exceeds 1 ton/ha, and the polyurethane foam blocks are reused up to 5 years, while the rockwool materials only last 2 years.

From the recycling point of view, some agricultural applications offered a market for the future use of recycled materials (fences, drainage tubes, and young-tree posts).

Residues

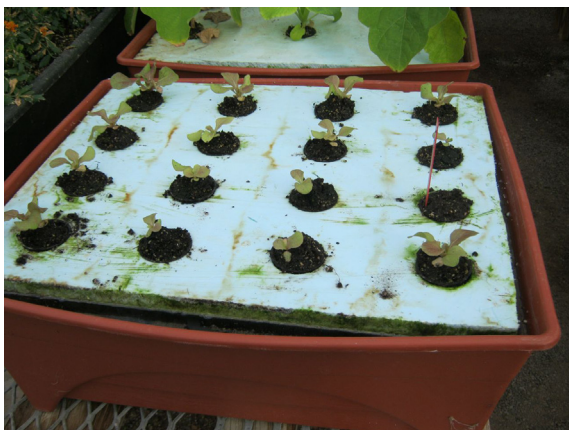
The thermoplastic materials used in agriculture and horticulture include a wide number of applications. Some of these techniques help in a better usage of natural resources, like water in localized irrigation, and other uses are environmental-friendly relative to conventional agriculture techniques (like soil solarization that reduces the use of pesticides).

The greenhouse industry generates internal residues, as other agricultural activities, that affect soil and water and external wastes, such as plastics and plant biomass debris. Almost all of the plastic waste from the greenhouses is recycled. Plant debris may be disposed in many ways, such as being composted, land-filled, burned (under control with energy recovery), or used in biofumigation (technique of soil pathogens control through the action of volatile compounds produced during the decomposition of the organic matter from some plant biomass debris). The environmental impact of fertilizer water leaching from irrigation of greenhouse crops is a factor requiring improvement. Relevant studies and efforts on that subject have been conducted and the recirculation of leaching water in soilless-grown crops is extended.

Good Agricultural Practices—Integrated Pest Management

The stabilization of the production area in the European greenhouse industry has been followed by the generalized adoption of good agricultural practices and integrated production and marketing programs, driving protected European horticulture toward more environmental-friendly systems. Enhanced environmental control is one of the aspects that have improved in the greenhouses of the European protected vegetable and flower growers. The massive implementation of integrated pest management in greenhouse crops is a major step forward to guarantee the sustainability of European greenhouse production.





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2 Plastic Film Production

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Introduction

The process of converting plastic from the form provided by the material suppliers into plastic film looks simple, but there are several complex phenomena that influence the final product. By manipulating several key polymer properties, different types of film can be produced. This can be done by using different processing equipment, as well as varying the processing parameters. All of these elements are used to change polymer film properties.

The film process starts with an extruder, which is a machine that melts and pumps the plastic. The molten plastic is pumped through a die that forms the melt into a thin sheet of plastic. From here, the process changes depending on the type of film being produced. At this point, the film can be stretched to give it the properties needed for the application. The film then has to be cooled and rolled on winders. The film bought in stores goes through some postprocessing steps to cut and fold or roll it.

While each film-making process can make a product with identical physical dimensions, the required performance of the film is the reason why there are several different processes used to manufacture it. The differences in each process are the materials' reaction to the unique process steps.

This chapter will cover the key polymer material properties needed for the manufacturing of the different films. Without basic knowledge of them, it will be difficult to understand how each of the process steps works. Much can be written about the properties of polymers, because of their complex relationships between the molecules and the chemical makeup of the polymer. What will be presented here is a broad generalization to make these complex relationships easier to understand.

Polymer Properties

There are two types of polymers used in the manufacturing polymeric parts. They are thermoplastic and thermoset polymers. Thermoplastics are many long-chain polymers mixed together. The only thing needed to form the polymers into a part is heat. Once formed, it can be reheated and reformed into another part. Wax is a good example of a thermoplastic polymer. Wax is a short-chain thermoplastic polymer. Typically, wax has about 30 carbon atoms on its chain. Polyethylene is closely related to wax. The main difference is that polyethylene has several hundred thousand carbons on its chain. While they can be remelted many times, there is a practical limit to this. Because of the process to chip the polymer parts and the frictional forces used to melt the polymer during manufacturing, the length of the polymer chains is lessened from breaking of the covalent bonds on the polymer chain.

Significant remelting in the manufacturing process will make a long-chain polyethylene start to approach wax. When this happens, there is a significant reduction in polymer properties, which makes the part perform differently than a part made from new polymer. Generally, in industry, no more than 25% of the polymer used can be reground polymer. In most, if not all, food grade and medical parts, no reground polymer can be used.

The second type of polymer is thermosets. Thermosets start with very short-chain polymers that have bonding sites build into the polymer chain. Under heat or chemical reaction, the bonding sites seek another bonding site on an adjacent chain. As the reactions happen, the short chains build into a longer three-dimensional molecule or several sets of three-dimensional molecules. Once the forming process finishes, the part should ideally be one large molecule. In practice, that usually does not happen. There are still many bonding sites that cannot bond with any adjacent chains. After forming, the parts can be subjected to a “postbake” to allow the remaining bonding sites to find bonding partners.

Polymers are long-chain organic molecules that get their properties from the length of their backbone and the things that hang off that backbone. The backbone is the long central group of atoms that go from end to end. There are side chains, or side groups, that are attached to the polymer backbone. The reason polycarbonate is different from a polyethylene or a polystyrene is because there is something different either on the backbone or on the side chains. Even a small change can create a difference in how polymer behaves in either a solid state or a molten

state. Looking at an ideal polyethylene, the backbone is a series of carbon atoms present from beginning to the end of the backbone. The side chains are nothing more than hydrogen atoms coming from the other two bonding sites on the carbon atoms on the backbone.

A measure of the length of a polymer chain is molecular weight. It is used to calculate the number of atoms on the polymer chain. In large-scale polymerization of polymers, it is impossible to create polymer chains of identical length. There is a distribution of lower and higher chain lengths than the target chain length. It is not uncommon for a polymer material supplier to create slightly different batches of polymer, even if they use the same polymerization settings. This difference from batch to batch can have an effect on how the polymer is converted into a part. Each batch may require a process adjustment to bring the parts back into specifications. Depending on how well the polymerization process is controlled, the difference can be small (narrow distribution) or big (wide spec).

The molecular weight distribution is made up of lower and higher polymer chain lengths. Each one has some effect on the performance of the polymer. Lower-molecular-weight components have shorter polymer chain lengths, which result in less entanglement. These components will flow easier (lower viscosity) when melted. Because of less entanglement, the polymer is not as strong as a higher-molecular-weight component, which will have more entanglement. The longer polymer chain lengths will also have higher melt viscosity.

A narrow distribution is when the majority of polymer chains are very close to the target chain length. This means that there are some higher- and lower-molecular-weight components, but they are so close to the target and will not change the polymer's properties significantly. Wide-spec material will have significantly lower- and/or higher-molecular-weight components that will significantly alter the processability and part performance.

One simple way to get a measure of the molecular weight is by the use of a melt index test. A standard melt index test measures the output in grams over a 10 min time period. If the polymer has a lower viscosity, the molten polymer will flow easily and have a higher melt index number. By comparing the melt indexes of two polymers from the same polymer material family, the one with a higher melt index indicates that it has a lower viscosity, meaning it has less entanglement. This would be a polymer with a lower molecular weight. There are also tests that can evaluate the polymer to determine the distribution and average molecular weight, but they are complex and expensive.

The interaction of the polymer chains can be likened to a plate of spaghetti noodles. This is the best analogy to understand how the polymer chains are entangled with each other. However, where the plate of spaghetti noodles analogy falls apart is the fact that the individual polymer chains do not act like limp spaghetti noodles. The polymer chains are not just mixed with each other. There is an attraction between the polymer chains. As the part is put under loading, the polymer chains will slide past each other in response to that load. Polymers, with big, bulky side groups like polystyrene, have difficulty with the polymer chains sliding past adjacent polymer chains. There are several types of molecular bonding in polymers. Covalent bonding is between the atoms on the polymer backbone and side groups. These are very strong bonds and are very difficult to break. Things like ultraviolet radiation can break those bonds and cause a loss of material properties. There are weak secondary forces between the polymer chains. These are an attractive force between the polymer chains and it holds them together. This force affects the material's behavior. When there is a lot of heat added to the part, the weak secondary forces start to break down and the space between the polymer chains gets bigger. This extra space gives the polymers some extra mobility to move. Going back to the spaghetti analogy, it would be as if the spaghetti noodles have cooled and started to dry out, which makes them sticky. Now they are entangled and are stuck together. When the polymer is cooler, the weak secondary forces are stronger and the polymer chains are held tighter. There is less molecular mobility and it is harder to get the polymer chains to slide past each other. In the molten state, where there is more heat, the weak secondary forces are very weak. This will allow the polymer chains to slide more easily past each other and flow easily. This is measured by the viscosity of the polymer. As the polymer's temperature is raised, it has less viscosity and flows more easily.

There are different types of polymer chains. The linear type is where the polymer chain has very short side chains. The next type is branched, where the polymer side chains are long. Even the linear-type polymers can have very short side chains, but the branching is not very long. A good example to show the different types is the polyethylene family. High-density polyethylene (HDPE) is a very semicrystalline material. Because of the very short side chains, it is easier for the polymers to slide past each other and form a dense crystalline structure. In medium-density polyethylene, the side chains are much longer and are more entangled with the other polymers. This makes it very difficult to form

a crystalline structure. In low-density polyethylene (LDPE), there are very long side chains that are even more entangled. This extra entanglement makes it more difficult for the crystalline structure to form. The next variation is linear LDPE. In this case, the side chains can be almost as long as the polymer backbone. This creates even more entangled side chains than LDPE. There is less chance for crystalline structures to be formed. For each variation on the side chains, there is a significant property change. In HDPE, the polymer is very strong but not very flexible. In LDPE, the polymer is more flexible and has a lower strength than HDPE. In the polyethylene family, all of the variations have the same backbone and the same side chains, but the change in property comes from length of the side chain.

There are two types of thermoplastic materials: amorphous and semicrystalline. Amorphous materials are simply like a plate of spaghetti noodles. They are just mixed around each other and they do not form a crystalline structure. The amorphous polymers would like to form a crystalline structure, but the atoms that make up the polymer backbone, their side chains, and their entanglement prohibit them from doing so. In semicrystalline materials, there is a tendency for the polymer chains to start folding onto themselves to create a dense crystal structure. The crystal structure that is formed is a complex three-dimensional structure of many polymer chains. Depending on how the polymer film is cooled, the structures can be small or large.

The forces to pull apart these crystals are stronger than just the weak secondary forces between the polymer chains. The crystalline structure has the initial polymer chain and some adjacent polymer chains as part of the structure. This creates a denser structure than what would happen if the polymer chains were entangled like simple spaghetti noodles. Because of how the structures are formed, the crystalline structures cannot pull all of the polymer chains into the structure. This creates some amorphous regions between the crystalline structures. The amount of amorphous regions can be manipulated by how the polymer is processed during the forming of parts.

While the basic properties are a function of the polymer's chemical makeup, some properties can be influenced by how the polymers are processed. The amount of crystallinity is determined by how the film is processed. Temperature plays a big role in the amount of crystallinity. The longer it takes to cool the film, the polymer chains will have more time to form crystals. As long as the polymer is above its melting temperature, the lower viscosity makes it easier to form more and larger crystals.

The other property that is processing-dependent is orientation. Orientation is the ordering of the polymer chains in the direction of flow or stretching. Using the spaghetti analogy again, take two forks and drop them into the center of a plate of spaghetti noodles. Move the forks away from each other and watch how the spaghetti noodles line up to each other. Besides lining up in the direction of the applied force, the spaghetti noodles also disentangle themselves. During the flow of the polymer in the die, some orientation will occur in the direction of flow. It will line up the polymer chains because of flow differences inside the die. In areas with high velocity differences, the polymer chains will look a lot like the spaghetti noodles in the fork example. It is the forming steps, before the polymer cools, outside of the die that cause more orientation. By stretching the film in the flow direction and perpendicular to the flow direction (biaxial orientation), a film with much more strength can be created. Film can be made with little or no orientation (monoaxial orientation) or biaxial orientation. Each one behaves differently.

Orientation can give strength to the film. Continuing with the spaghetti theme, imagine that you have just put four jars of pasta sauce in a plastic grocery bag. Those bags are biaxially oriented. When you lift the bag, there is a little stretching around the handle region and the bottom of the bags that touch the jars. This is the polymer orienting a little more under a heavy load. Once this secondary stretching is done, the jars can be lifted and transported. If the bags were made from unoriented film, you would be pulling the handles up very high to create enough orientation to get the strength needed to get the jars to lift from the table.

The spaghetti noodle analogy breaks down when looking at how a single polymer chain behaves. While a spaghetti noodle will hang limply when dangled by one end, a single polymer chain will not do so. During the polymerization process, small monomers are covalently bonded to each other to create the long chain. When atoms are covalently bonded to each other to create large molecules, there is a bond angle between the two connecting atoms. In a polymer, these bond angles cause the polymer to roll or fold up on itself. When the polymer is stretched, it wants to pull back to its original folded position. There is a force that is created when the polymer is stretched or oriented.

A single polymer chain can be looked at as behaving as a spring. When a polymer chain is stretched, it wants to go back to its natural state with the bond angles that were created when the polymer was polymerized. These forces are always present, because the monomers

that undergo polymerization do not make individual chains and are mixed together later to make a mixture of the polymer chains. All of the polymer chains are created in one big batch. As the polymerization occurs, the polymer chains entangle with adjacent polymer chains as they grow in length.

When there is orientation present in a part, the forces from the orientation will be imposed on the part will most likely be manifested as warpage. Although it is not the only phenomenon to create warpage, it is usually responsible for at least a small portion of the warpage. It is impossible to create a part with thermoplastic polymers without some amount of orientation. There are some annealing processes that can reduce the amount of orientation, but these are usually done outside of the basic polymer processing steps.

After forming, there are some important performance criteria to be considered with regard to the film. Just as the polymer chains can flow past each other when it is above its melting point, the polymer chains can flow even when they are cold. This is called “cold flow,” which is a time-dependent phenomenon. In order for the polymer chains to cold flow, they have to slowly unentangle themselves and start to slide past the other polymer chains that they are entangled with. This occurs when an external force is applied to the film.

Another consideration with orientation in a film would be the function of temperature. Temperature directly affects the weak secondary force between the polymer chains. When heat is added, the atoms in the polymer increase their internal energy. The increase in internal energy will decrease the weak secondary force between the polymer chains. Conversely, a high weak secondary force will attract the polymer chains and create a tighter, denser structure. Cold flow is very difficult in this case. It takes more force to get the polymer chains to slide past each other. Imagine the spaghetti noodle analogy with butter or oil mixed in. In the refrigerator, the butter or oil becomes thicker and stickier and it is hard to pull the spaghetti noodles apart. If the plate of noodles is then heated, the oil becomes less sticky and allows the spaghetti noodles to easily move. This is essentially what happens to the polymer. It is the distance between the polymer chains that dictates how much cold flow will occur.

When the polymer experiences higher temperature, the lower weak secondary force creates more distance between the polymer chains and allows the polymer chains to slide past each other easily. This allows for the polymer to more easily cold flow. The easier flow can be either from an external stretching force or from the oriented polymer chains

wanting to return to their natural state. A good example of this is shrink tubing or wrap. The film is highly oriented in one direction (monoaxial orientation). As the film is heated, the weak secondary forces decrease and create more space between the polymer chains. At a certain temperature, the weak secondary forces relax enough to allow the orientation to relax. When that happens, it reduces dimension in the oriented direction.

As the temperature is further increased, the weak secondary forces are more weakened and the polymer will be in the molten state. In semicrystalline materials, the reduction of the secondary forces also eliminates the forces that create the crystals and the polymer now resembles an amorphous polymer.

There are three main considerations when evaluating the cold flow of a film: temperature, loading rate, and crystallinity. While the film's polymer will cold flow at room temperature, an increase in temperature will weaken the secondary forces between the polymer chains and make it easier to cold flow. Examples of where this impacts the performance would be where the film holds a load on a cold day, but fails on a hot day, or it would stretch less on a cold day and more on a hot day. The rate that the load is applied is also important. At the same temperature, a load that is slowly applied will allow the film to cold flow to react to the load. When the same load is quickly applied, the polymer chains do not have enough time to react to the load and the film may fail. A highly crystallized film will be stronger but will be more resistant to cold flow.

Extrusion

The root of the word “extrusion” is based on the Greek word for “push out”. While this is true for the extruder, it is not true for the whole extrusion line. In a basic extrusion setup, the extruder pushes the molten polymer out of the die. Beyond that, pulling is needed to move the molten plastic to the final station. The process of extrusion covers many different types of processes. Film and sheet are the biggest processes by volume in extrusion. The other types of extrusion are profile, piping, wire coating, and fiber spinning. Each of these different types of processes utilizes the same basic elements of the extrusion line, but they use them in a different fashion.

Because the extruder pushes molten polymer through a die, it only allows the process to make parts with a two-dimensional cross-section.

To get features in the third dimension, sometimes postforming processes are used to create limited shapes in the parts. There is a specialty process that creates the corrugated pipe, but the three-dimensional shapes are limited.

Profile extrusion can be used to create anything from simple piping to complex shapes, such as window profiles, beams, wipers, and beyond. The die design in these types of parts can be difficult. They are typically made from several die plates. The first plate moves the circular cross-section of the barrel and begins moving it to the shape of the part. There can be one or more intermediate plates to adjust the flow in the die. The last section is the land; it sets the final shape of the part. The ideal situation is when the molten polymer exits every section of the die at the same velocity. A uniform wall thickness part is an easy die to make. There are very few adjustments necessary to get uniform flow out of the die.

Once the molten polymer leaves the die, it enters a water bath through a sizing die. The molten polymer is drawn down about 30% of the die's shape before it gets to the sizing die. The sizing die holds the part's shape while it cools enough to hold its shape. The sizing die exaggerates the final shape because the molten polymer finishes cooling about a meter into the water bath. Before it cools, it can change shape. Once it leaves the water bath, it enters the puller. This is the device that pulls the molten polymer through the system after it leaves the die.

For the kind of parts that can be made in profile extrusion, there is no other polymer conversion process that could make the parts as cheaply as extrusion. The extrusion process is one of the simplest in polymer processing. The dies typically cost in the low thousands of dollars, whereas other processes would need a mold that would cost ten times more to make the same part. However, the other processes could make better-looking parts and hold a tighter tolerance. Debugging a die to get uniform velocity flow may take several weeks. It is usually a trial-and-error process to get the die to provide a part that meets specification.

The other extrusion processes are a variation on profile extrusion. They will either use a different die or puller system. In the following section, extruded film will be examined.

The Extruder

The process starts with the polymer material in either a powder or a pellet form. The most commonly used material is the pellet, approximately one-eighth inch in diameter. In most high-volume

manufacturing, the polymer material is brought to the factory in railcars or trucks and loaded into large silos. From there it is vacuum-fed to the manufacturing floor. It is loaded into a hopper on the feed section of the extruder. From here it is gravity-fed to the screw through an opening in the barrel, called the feed throat. The feed throat allows the polymer to enter the feed section of the screw. An Example of an extruder with a film die can be seen in [Fig. 2.1](#).

There is a control panel where the operator sets the barrel and die temperatures and extruder revolution per minute. The control unit monitors the extruder settings, motor load, and melt pressure before the die. It can also control the film line, if the extruder is bought as part of a turnkey system.

The extruder is a pump that converts solid polymer into melt. It is made up of several important units. The two most important items that do the conversion are the screw and the barrel. The screw fits into the barrel and has an extremely thin clearance. The screw has three sections, namely, the feed, transition, and metering. The feed section is where the polymer enters the screw. This section has the deepest channel on the screw. As the polymer moves along the screw, it goes into the transition section, where melting starts to occur. It is in this section that the channel gets shallower. The squeezing and the movement of the solid polymer create frictional heat. As the heat increases



Figure 2.1 Extruder with Film Die.

above the melting point, the solid polymer slowly begins to melt as it is being conveyed farther down the screw. Ideally, the polymer is completely melted at the end of the transition section.

The temperatures in the barrel are closely controlled to give the molten polymer the desired properties and strength to be extruded. There are heater bands and cooling fans to control the temperature in the three sections of the screw and the barrel. The heater bands are set up in zones. They are simple electric heaters that surround the outside of the barrel. A series of thermocouples read the temperature. If the heat is too low, the temperature controllers supply electricity to the heater bands or cartridges and turn them off when they are close to the controller's set point.

In the feed section of the barrel, the temperatures typically are lower to create more friction and facilitate melting earlier in the screw. The heater bands are not responsible for the energy needed to melt the polymer. The frictional heat from the conveying and squeezing of the solid polymer can generate temperatures in excess of the set points for the heater bands. Usually fans, cold oil, or water are used to bring the temperature down to the set point when this happens.

The last section of the screw is the metering section. It has the shallowest channel in the screw. Since the polymer is almost completely molten in this section, the feed section acts like a pump and pushes the material out towards the die. At the end of the extrusion barrel is a breaker plate and screen pack. The breaker plate is used to stop the swirling action of the molten polymer as it leaves the screw. It also supports a screen pack, which is a series of screens used to filter contaminants that may have been introduced into the hopper. It is not uncommon for jewelry or metal fasteners to fall into the solid polymer stream.

A motor connected to a gearbox is used to provide rotation to the screw. The speed that the molten polymer is pushed out of the die is regulated by the screw's revolution per minute. At higher revolutions per minute, the speed with which the solid polymer is conveyed through the feed and transition sections of the screw is increased, which increases the frictional heating. This, in turn, helps to melt the polymer more quickly. As a general rule, film producers like to run at the maximum revolution per minute to increase their profitability.

The Die

The last item on the extruder is the die. There are two different processes used to form the molten plastic into film: flat film and blown film. Each one uses a different die. Flat film is better at providing quick

and more uniform cooling to the film after extrusion. Flat film is capable of high output rates and has more uniform thickness. However, flat film is limited in the practical width of the film. Blown film has a lower output rate than flat film and has less control on its thickness variation. Blown film can generally make wider film than flat film processes.

Regardless of die used in the different film processes, the die's last section is the land. The land is a continuous cross-section used to fix the final shape of the molten polymer as it exits the die.

Inside the die, the molten polymer's orientation is dictated by how the molten polymer flows. Because polymer that flows against the die walls experiences drag resistance from the walls, it flows more slowly than the polymer in the middle of a flow channel. This creates a velocity difference between the center of the flow to the die walls. Although the molten polymer does not flow in layers, describing the flow in layers is an easy way to understand what is happening. When looking at Fig. 2.2A, the velocity from the center of flow to the die wall can be seen. Because of the drag flow near the die wall, the velocity is very low. Depending on the pressure on the molten polymer at that section of the die and the velocity of the molten polymer in the center of the flow channel, the velocity could be zero. Generally, it is above zero and flows along the die. Fig. 2.2B shows a measure of the amount of velocity difference called shear rate. In Fig. 2.2C, temperature increase in the high shear rate areas are seen.

The highest velocity difference is experienced between the layer next to the die wall and the next layer in. This velocity difference creates shear differences between the layers. This shearing stretches the polymer chains in the direction of flow. This stretching is the process of orientation of the polymer chains. As it orients, the polymer chains disentangle themselves from their neighbor polymer chains. Layers that experience any velocity difference with an adjacent layer will create orientation. The polymer chains that are at the interface between the two layers are dragged along and stretched in the direction of flow by

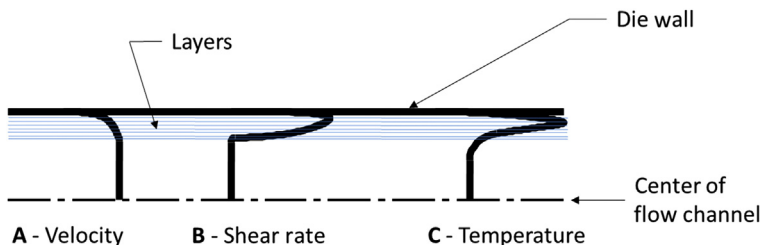


Figure 2.2 Effects of differing velocities on polymer.

the higher velocity layer; this is the cause of the orientation. In the areas closer to the die wall, the higher velocity difference can be seen. As the layers get closer to the center flow, the velocity difference is very low. As the main center flow usually travels at the same velocity, there is no velocity difference.

One of the outcomes of the velocity difference is an increase in temperature in the high shear rate layers. This is due to the frictional heat generated by the velocity differences between the layers. Unlike the extruder, where there are fans to cool the barrel, there is no way to cool the die. The dies do not have cooling devices, such as fans, to bring the temperature down. There are just heater bands or cartridges that supply heat to the dies. The temperature controller simply turns them on and off depending on thermocouple's reading.

One last effect of temperature is a phenomenon known as die swell. Die swell is mainly caused by the die's geometry. However, it can be influenced by temperature and the polymer's material properties. When the molten polymer exits the die and no longer has the die's metal to hold it to shape, the orientation from flow requires the relieving of the forces built up from orientation. This relieving is a local thickening of the molten polymer as it exits the die. When the die land is longer, it allows the orientation to be "locked in" as it exits the die because the orientation has a longer time to adjust to the new shape and polymer chain alignment. This will result in lesser thickening when it exits the die. Temperature can also cause a difference by altering the strength of the weak secondary forces. A hotter melt will have more space between the polymer chains because of the lower weak secondary forces. The hotter melt will allow the orientation to relieve more once it exits the die. Another influence on the amount of swell is the velocity of the molten polymer as it exits the die. A higher velocity will increase die swell because the polymer chains cannot spend as much time adjusting to the new polymer chain alignment. When it exits the die, it will swell more to relieve as much of the orientation as it can.

Flat Film Extrusion

For flat film applications, a "coat-hanger die" is used. As would be expected, the shape of the molten polymer channel in the die looks similar to a coat hanger. The outlet of the die is rectangular, with the width being long and the height being very thin. The ideal flow out of the die is that all areas of the rectangular opening have a uniform velocity. The

shortest flow path is directly in front of the inlet from the extruder barrel. Inside the die, there can be a thin section across the flow channel to act as a dam. The thickness of the flow channel can be manipulated to promote flow to the outer edges of the flow path. One final way to balance the flow is a flexible lip that can be manipulated by a series of adjustment screws at the outlet of the die. This affects the flow in the land section of the die.

Care must be taken to ensure that the adjustments do not affect the die swell across the opening of the die. Once the molten polymer exits the die, the thickness is set. Even though there is a drawdown of the polymer to create higher orientation, it is the thickness across the film as it exits the die that will set the thickness of the final film after stretching.

The coat-hanger die generally has cartridge heaters in the main body of the die and heater bands on the feeder sections that attach to the extruder. These control the temperature of the molten polymer as it flows through the die. There are several zones within the die that aid in acquiring the best polymer properties from the film as it is stretched after the die and for adjusting the flow in the die.

There are three types of film that can be produced with the flat film process. They can be unoriented, called cast film, monoaxially oriented, where they are stretched in the direction of flow, or biaxially stretched. Each process has different equipment downstream from the die. These processes utilize large amounts of floor space due to the many rolls used to process the film after it leaves the die. Sometimes the rolls are set up in a vertical orientation to save floor space.

The cast film process has the molten polymer coming from the die and cooled on chilled rolls in order to leave it in a relatively unoriented state. The only orientation is from the flow of the polymer through the die. Depending on how much the molten polymer swells when it exits the die and how quickly it is cooled, some of this orientation can be relaxed before the film fully cools. In cast film, the coat-hanger die generally is oriented to push the molten polymer straight down toward the ground. It is pulled onto a chromed steel roll that is perpendicular or is in cross-machine direction to the molten polymer flow, where the film is cooled on one side. An example of chilled rolls can be seen in [Figs. 2.3](#) and [Fig. 2.4](#). It then transitions to another parallel roll that cools the opposite side of the film. At a point before the molten polymer touches the first roll, an air knife is used to gently blow cool air onto the length of the molten polymer. This is used to quench the film before it cools on the rolls and to ensure it makes good contact with the

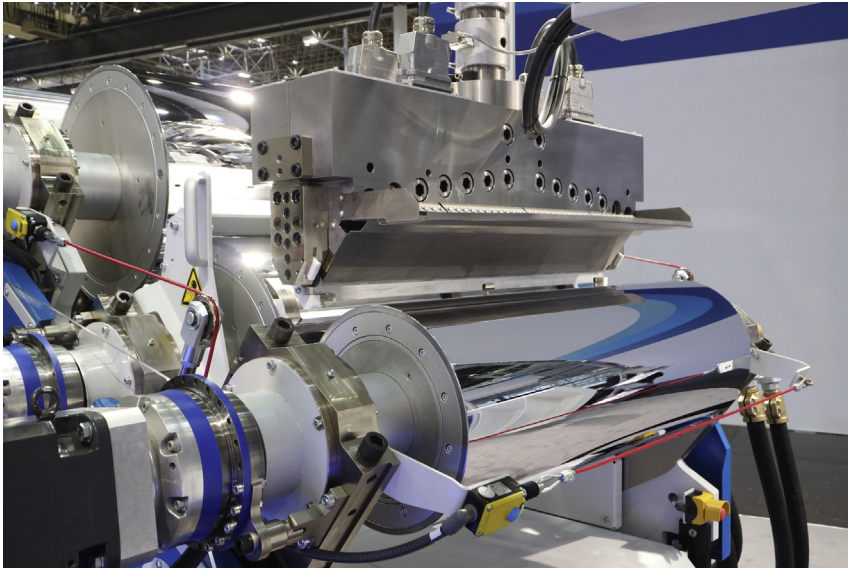


Figure 2.3 Flat Film Rolls.



Figure 2.4 Flat Film Rolls.

roll. If there is no air knife, a vacuum box is placed on the other side to ensure the film makes good contact with the roll. The rolls are wider than the width of the film.

There are cooling passages that run lengthwise throughout the roll. A chiller is used to pump coolant through those passages. This is needed to keep the rolls at the required temperature to solidify the film. It then passes through more rolls that position it for edge

trimming. The trimming is necessary because of how the polymer exits the die. The edges can be thicker or thinner than the middle of the film and it will affect how the film rolls up later on the winder. These films have a very soft feel. Compared to oriented film, which will tear in the direction of orientation, unoriented films have better impact and tear resistance. They are good for bread and produce packaging.

The next process is monoaxial orientation. In this process the film is cooled and the temperature is stabilized before any stretching occurs. Once cooled, the film is then stretched in the machine direction (the direction of flow from the die to the winder). It is this cold flow forming that increases the orientation in the film. Since the film is going to draw down to make a longer and wider film, the molten polymer that exits the die is many times thicker than the final product to account for that stretching. The molten polymer is extruded straight out of the die in the machine direction and picked up by the first set of rolls. These rolls are a lot like the chill rolls in cast film and are mounted lengthwise in the cross-machine direction. They are used to bring the temperature down to quench the film. The film then enters a set of rolls to bring the film up to the drawing temperature. The temperature is controlled by separate chillers for a cooler temperature or thermolators for warmer temperatures.

The film then moves to the draw rolls. There are several chromed steel rolls, each one with a rubber-coated nip roll to pinch the film and keep it from slipping, that are used for the stretching. Each chromed roll rotates faster than the one before. These draw rolls pull the film and stretch it ten or more times the original length. The next set of chromed rolls reduces the temperature slowly to lock in the stretch, while the last set of chromed rolls cools the film before winding. The edges are trimmed before winding.

Some uses for these types of film are shrink-labeling, food wrap, and diaper liners. While the monoaxial film will tear easily in the machine direction, the cross-machine direction tear strength is very good. It will be stronger than the biaxially oriented films, which will tear at an angle between the machine and cross-machine directions.

The last type of flat film is biaxially oriented film. After the film's temperature is stabilized, the film is pulled more in the machine direction and is also stretched perpendicular to the flow direction or cross-machine direction. This biaxial stretching can occur sequentially or simultaneously.

In the sequential process, the film goes through the same set of rolls that the monoaxial film uses before moving to the cross-machine direction stretching. Once the film is highly oriented in the machine

direction, the film is then conditioned again before moving to the cross-machine direction stretching machine called a tenter frame line. Here a set of clamps, called tenterhooks, grabs the edges of the sheet and progressively pulls the film to make it wider. The tenterhooks are attached to an endless chain that moves on a track that angles away from the machine direction. This angle sets the amount of stretching in the cross-machine direction. The chain pulls the film at the same velocity it comes out of the machine direction stretching machine. Once the tenterhooks release the film, it goes through a set of chrome rolls for quenching and cooling. Another set of rolls is used to position the film for edge trimming before being wound.

In the simultaneous stretching process, there is no separate machine direction stretching unit. After the molten polymer exits the die, it goes through several chromed steel rolls to quench the film and set the film's temperature before being stretched. The film enters the tenter frame unit where the tenterhooks grab the film. Unlike the sequential process where the tenterhooks in the track move at the same machine direction speed, the tenterhooks speed up in the angled section of the track. This makes the tenter frame pull in both directions at the same time to stretch the film. Another set of rolls is used to position the film to have the edges trimmed before being wound. It is claimed that a better balance of properties can be obtained with this simultaneous process.

Biaxially oriented film has a good balance of strength and barrier properties. Typically, these products are used in food packaging and bags. The film can be stretched up to five times longer in the machine direction and up to eight times in the cross-machine direction.

Blown Film Extrusion

The second main process for making film is blown film extrusion. This process uses compressed air and a set of nip rolls to stretch the film. Unlike the flat film process, there is no protection from the factories environment. This process utilizes the least amount of floor space, but it needs a lot of height. Some of the high output blown film towers are several stories high. An example of a Blown Film Tower can be seen in [Fig. 2.5](#).

Here a tubular die is used instead of a coat-hanger die. The tubular die converts a solid flow of molten polymer to a hollow tube of molten polymer. The outlet of the tubular die is at 90 degrees to the direction of the extruder and aims the molten tube, referred to as the bubble, up

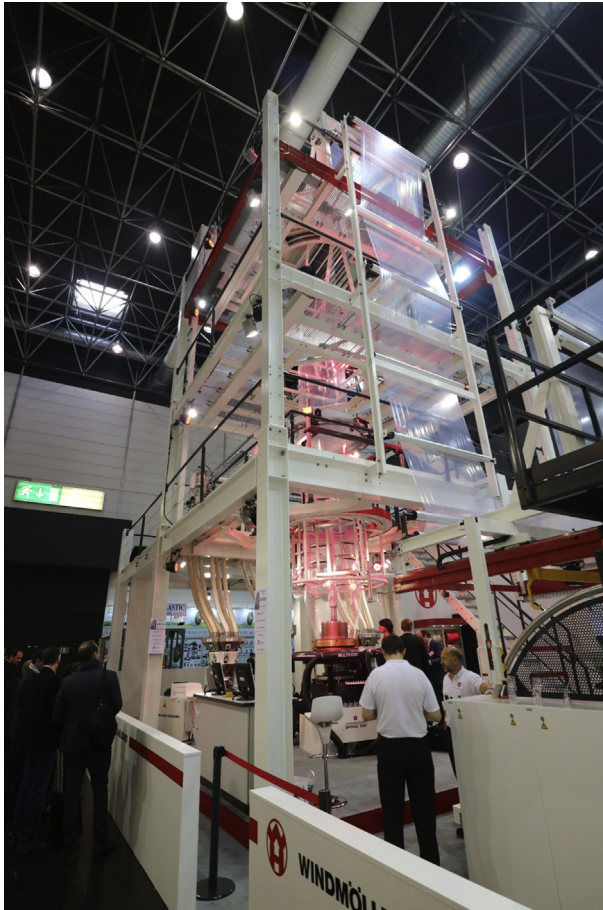


Figure 2.5 Blown Film Tower.

in a vertical direction. The thickness of the molten polymer is more than the final film. Because of the possibility of some variation in thickness, the die land rotates during the extrusion of the bubble. This helps keep the film flat on the winder. If a thick section stayed in the same place, it would create a hump on the final roll on the winder.

After the molten polymer exits the die, it experiences a pull from the overhead nip rolls at the top of the blown film tower. Depending on the material, the molten polymer keeps the shape and size of the die land. The region where the molten polymer keeps the die shape is called the stalk (Fig. 2.6). This region is important because it allows the molten polymer to cool before being stretched in the hoop (circumference)



Figure 2.6 Example of a stall before being blown to size.

direction. Materials such as LDPE do not need to cool much before stretching, so the stalk is very short. HDPE needs to be cooled more and has a stalk that is about eight times the die diameter height.

The inside of the tube is pressurized and is regulated by the control panel setting. This makes the tube expand in diameter above the stalk. This is the point where the stalk gets thinner and the air pressure can push the molten polymer to form the film. At the top of the machine, there is a nip roll which pinches off the top of the bubble and pulls the film up to the top of the blown film tower. The nip rolls keep the air inside the bubble. The air pressure inside the bubble is one of the processing parameters that are responsible for the bubble's diameter.

There is an air ring attached to the top of the tubular die, with an insulating plate between them. It blows cool air on the outside of the bubble to chill and size the bubble. Another way to cool and size the bubble is to circulate cool air inside the bubble. This internal bubble cooling is used to increase the amount of cooling provided to the bubble.

For semicrystalline materials, there is a “frost ring” that occurs when the molten polymer transitions from molten to a solid polymer. It is at this point that the bubble has mostly stopped growing in diameter. The film can be stretched up to four times the original length and diameter in this region.

The height of the tower is generally very high. High production blow film towers can be several stories high. This height is required to ensure the film is cooled before it enters the nip rolls. Because the bubble’s outside and inside temperature is influenced by the temperature of the air in the manufacturing plant and by any air circulated inside of the bubble, respectively, the height is required to cool the film before it can be collapsed to a lay flat. If it is not cooled enough, the two sides of the film will weld together. Because of the height, stabilizer cages are used to keep the bubble centered as it works its way to the nip rolls. If the bubble is not stabilized, it can be blown around by air drafts in the manufacturing facility. When this happens, the bubble is pulled to one side and it stretches the molten polymer on the other side. This creates a severe difference in thickness. The rollers on the stabilizer cage are generally coated so that they do not scratch or wrinkle the film. Some stabilizer cages are noncontact by using a steady flow of air to keep the bubble centered.

Right before the nip rolls, the guide rolls, or tent frame, are used to collapse the bubble into a flattened bubble, called a lay-flat. The guide rolls are a series of slats or rollers that progressively take the circular cross-section and convert it to the lay-flat. It is important to have the height and angle of the guide rolls set correctly to ensure that the film will not wrinkle as it enters the nip rolls.

The nip rolls seal the air in the bubble and their rotation is what pulls the bubble from the die to the top of the blown film tower. One roll is fixed in position while the other roll is pneumatically moveable to allow ease of startup. The fixed roll is generally a chromed steel roll, whereas the movable roll is generally a rubber-coated roll. Once it passes the nip rolls, the lay-flat undergoes additional cooling before being wound. This is accomplished by having the lay-flat wind through several rolls, and in essence, lengthening the time before it is wound.

Additional Film Production Considerations

In high volume production, two or three extruders can be used to push the polymer into the dies for both flat-film and blown-film applications. In these processes, very high line speeds are needed to move the polymer from the die to the winder. This complicates the temperature stabilization because of the increased speeds and shorter times available to control the temperature.

Both flat film and blown film can be made with multiple layers. Multilayer dies have inlets that are fed by multiple extruders, with each extruder feeding in a different material. Because of the very viscous nature of polymers in the melt state, the different materials do not mix when put together and stay in the same layer where they are placed. This makes it easy to create the multiple layers. The base layer is generally the inside or bottom layer. Each additional layer is another opening in the die above or outside of the layers that have already been put together in the die. The last layer forms the top or outside of the film. Typically, these additional layers are used for barrier properties in films. Depending on the polymers used, sometimes a layer is used to tie or bond two layers together.

Main Processing Parameters

There are two main processing parameters that are important in the formation of film. The first is temperature. The temperatures that are needed for the basic extrusion process facilitate easy flow of the molten polymer through the die. Because of the frictional heating that occurs, the temperatures can go above the extruder's set point. This is not desirable because there could be some degradation of the material when it goes above a critical temperature. If the molten polymer is at a higher temperature, it will take longer to stabilize the temperature before any process-induced orientation can take place. The temperature is critical in monoaxial- and biaxial-oriented films because it changes how much orientation can be put into the film. After orientation, the temperature is still critical. If the newly formed film's temperature is too high, some of the process-induced orientation will be reduced. The higher temperatures decrease the weak secondary forces between the polymer chains and allow them to flow back past each other to recover from the stretching.

The speed difference between extruder and puller, as well as the distance the film is stretched after it comes out of the die, will determine the

amount of orientation in the film. When the film is pulled faster than the extruder speed, the stretching will line the polymer chains in the direction of stretch. In the cross-machine direction, for biaxial orientation, the distance it is stretched determines the amount of orientation in that direction.

In blown film, there is another processing parameter that is important: bubble air pressure. It is used to set the basic diameter of the bubble. By having a higher bubble pressure, it is possible to make a bigger bubble. Air pressure is not the only processing parameter in blown film. The difference in extruder or nip roll speed also has an effect. A faster extruder revolution per minute or slower nip roll speed will create a thicker film. The thicker film puts up more resistance to the air pressure and it cannot be pushed out as far, so it creates a smaller diameter bubble. Another influence on the bubble's diameter is the air ring. It blows air onto the outside of the bubble. If it cools the molten polymer too soon, the bubble will not be able to grow as much in diameter. The temperature of the air coming out of the air ring also has an effect.

One of the key measurements done to film is to measure the thickness. No matter how closely they watch the process, it is impossible to keep the thickness of the film constant. There is always a thickness distribution across the width of the film. In most high production film lines, there is an inline measuring system to monitor the thickness distribution across the width of the film. These machines typically have a spot-checking sensor that reads the thickness by using noncontact capacitive or infrared sensors. For flat film, the spot sensor is on a track that moves back and forth across the width of the film. It continually monitors the thickness. In blown film, there are two ways to measure the thickness. The first is a rotating sensor located just above the point where the bubble diameter stabilizes. It works like the flat film sensor, except that the track is circular. The second way is to measure the film after it becomes a lay-flat. The rotating sensor is the only one of the two that can give position feedback for troubleshooting a problem.

Some systems use the data from the sensors to make automatic corrections to the process. Once the data are read, the system evaluates the thickness change and reads the processing parameter's actual readings. In a smart system, it determines what the problem is and tries to correct the situation. It usually will change temperature zones in a die or it can modify the die opening if it has an automatic system to do so. In blown film, the airflow through the air ring can also be used to modify the thickness distribution.

The causes for this variation in both flat film and blown film are twofold: thermal shrinkage and die gap differences. In blown film,

another cause for variation is the bubble being off-center from the die. Temperature differences during the forming and stretching of the film affect the viscosity in the die and the weak secondary forces in the film as it is being oriented. The change in viscosity inside the die creates changes in how the molten polymer flows through the die. The areas where the molten polymer has the least velocity will be the areas that will flow faster. Those areas will have the preferential flow and will be thicker than the slower areas.

Outside of the die, temperature still has a big effect on the thickness distribution in the film. As the force is put on the film to stretch, from air in blown film or tenterhooks or rolls in flat film, the areas of the film that will stretch first will be those that are hotter. The higher heat will cause the weak secondary forces to be less and will allow that area of the film to stretch easier. Although there is some amount of factory environment control and some of the processes have covers for the forming areas, small changes in temperature or humidity will have large impacts on the film production. Blown film is more susceptible to this because the bubble is open to the environment.

The die gap can be used to adjust the flow, but it can also affect the thickness. A balance between even flow and thickness distribution needs to be taken into account to get the best film thickness distribution. Changes in velocity and die swell create the potential for non-uniform thickness across the width of the film.

Conclusion

By manipulating the polymer's properties, several different types of film can be produced. Each one performs differently. Each type of polymer film process steps manipulates the polymer chains to create unique orientation patterns.

Orientation provides strength. Biaxial orientation allows for uniform strength across the film. Monoaxial film has strength in one direction but is weaker in the other. Orientation, as well as higher crystallinity, can decrease vapor transmission through the film. Depending on the desired film characteristics, there can be a film that fits your application.

3 Plastic Mulches for the Production of Vegetable Crops

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The development of polyethylene (PE) as a plastic film in 1938 and its subsequent introduction as a plastic mulch in the early 1950s revolutionized the commercial production of selected vegetable crops. Throughout the succeeding years a tremendous amount of research has been conducted by research and extension personnel located at the Land Grant Institutions in the United States in close cooperation with industry personnel representing the various companies that manufactured the plastic mulches, together with growers, documented the advantages of using plastic mulch as one component of a complete “intensive” vegetable production system. Although a variety of vegetables can be grown successfully using plastic mulches, muskmelons, honeydews, watermelons, squash, cucumbers, tomatoes, peppers, eggplant, okra, sweet corn, and cole crops including pumpkins have shown significant increases in early harvests, total yield, and quality.

Research continues on field evaluation of new formulations of biodegradable, wavelength selective, and colored plastic mulches and on cropping systems to best utilize these specific improvements. The use of plastic mulches for the production of vegetable crops continues to increase throughout the United States and the world.

The cornerstone of the “intensive” production systems for vegetables, such as muskmelons, honeydews, watermelons, cucumbers, squash, peppers, eggplants, tomatoes, okra, sweet corn, and cole crops (in both single and multiple cropping situations), is plastic mulch. In addition, however, the complete production package includes drip irrigation, fertigation, containerized transplants, grain windbreaks, row covers and a sound pest control program (Photo 3.1). Plastic mulches provide many positive advantages for the user, such as increased yields, earlier maturing crops, higher quality produce, insect/disease management and weed control and allows other components like drip irrigation to achieve



Photo 3.1 Plasticulture field of staked tomatoes.

maximum efficiency. Today, over 114 million pounds of plastic mulch is used annually in the United States (Ennis, 1987) and the number has surely risen to 175 or 200 million pounds since that figure, although obtaining reliable data is hard to come by.

One of the first plastics produced on a commercial scale in 1939 was polyethylene (PE). The widespread use of PE in agriculture and more specifically plastic mulches is due to its easy processing, excellent chemical resistance, high durability, flexibility, and freedom from odor and toxicity as compared to other polymers (Wright, 1968). The polyethylene resin comes to the manufacturing facility in the form of pellets, which are converted into flexible sheets of plastic film by either the “blown bubble” process or the “slot casting” method (Clarke, 1987). The main PE used in mulches is low-density PE (LDPE), which is produced by the polymerization of ethylene under very high pressure. It has excellent tensile strength, which is required for mechanical application of the plastic mulch to the soil and to resist tearing when exposed to strong winds and foot traffic.

Various additives are incorporated into the plastic to modify or enhance some specific property of the finished product. These can include pigments for color, slip agents, antiblock agents, antioxidants, ultraviolet (UV) inhibitors/stabilizers, flame-retardants, and photodegradable additives (Wright, 1968).

Specifications

Most of the plastic mulches used in the United States are 1.25 mil (0.031 mm) thick and 48 in. (122 cm) wide and come on rolls 2400 ft (731 m) long. The width of the plastic mulch may vary from 36 to 60 in. (91–152 cm), depending on the crop and cropping system. The most common width is 48 in. The plastic mulch will be either smooth or embossed with a diamond-shaped pattern that helps reduce expansion and contraction that results in loosening of the mulch from the raised bed ([Photo 3.2](#)).

Importance of Color

The color of mulch determines its energy-radiating behavior and its influence on the microclimate around the vegetable plant. Color determines the surface temperature of the mulch and the underlying soil temperatures. Much of the early pioneering research by Dr. Emery Emmert (known as the Father of Plasticulture) ([Emmert, 1957](#)) on the use of plastic mulches for vegetable production was to define the impact different colored mulches had on soil and air temperatures, moisture retention, and vegetable yields. Other researchers ([Shadbolt, 1961](#); [Schales and Sheldrake, 1962](#); [Blackhurst, 1962](#); [Takatori et al., 1964](#); [Tukey and Schoff, 1963](#); [Waggoner et al., 1960](#)) worked mainly with three colors, namely, black, clear, and white. These colors still predominate commercial vegetable production today, although white has been replaced largely by a coextruded white-on-black ([Photo 3.3](#)).



Photo 3.2 Muskmelon transplant on raised bed covered with black plastic mulch.



Photo 3.3 Clear and black mulches with drip irrigation being tested with a muskmelon crop.

The soil temperature under plastic mulch depends on the thermal properties (reflectivity, absorptivity, or transmittancy) of a particular material to incoming solar radiation (Schales and Sheldrake, 1963). Black plastic mulch is an opaque black body absorber and radiator, absorbing most UV, visible, and infrared wavelengths of incoming solar radiation and reradiating absorbed energy in the form of thermal radiation or longer wavelength infrared radiation. Much of the solar energy absorbed by black plastic mulch is lost to the atmosphere through radiation and forced convection. The efficiency with which black mulch increases soil temperature can be improved by optimizing conditions for transferring heat from the mulch to the soil. Because thermal conductivity of the soil is high relative to that of air, a large proportion of the energy absorbed by black plastic can be transferred to the soil by conduction, if there is good contact between the plastic mulch and the soil surface. Soil temperatures under black plastic mulch during the daytime are generally 5°F (2.8°C) higher at 2 in. (5 cm) depth and 3°F (1.7°C) higher at the 4 in. (10 cm) depth compared to that of bare soil. Black-colored mulch is predominantly used in US vegetable production systems.

By contrast, clear plastic mulch absorbs little solar radiation but transmits 85–95%, with the relative transmission depending on the thickness and degree of opacity of the polyethylene. The lower surface of clear plastic mulch is usually covered with condensed water droplets. This water is transparent to incoming shortwave radiation but is opaque to outgoing longwave infrared radiation, so that much of the heat lost to the atmosphere from a bare soil by infrared radiation is retained by clear plastic mulch. Thus, daytime soil temperatures under clear plastic

mulch are generally 8–14°F (4.4–7.8°C) higher at 2 in. (5 cm) depth and 6–9°F (3.3–5.0°C) higher at 4 in. (10 cm) depth compared to bare soil. Clear plastic mulches are generally used in the cooler regions of the United States but require an herbicide to control the weed growth that will result.

White, white-on-black, or silver reflective, or more recently metalized silver mulches may result in a slight decrease in soil temperature 2°F (1.1°C) at 1 in. (2.5 cm) depth or 7°F (4°C) at 4 in. (10 cm) depth compared to bare soil, because they reflect back into the plant canopy most of the incoming solar radiation ([Photo 3.4](#)). These mulches are used to establish crops like cauliflower or tomatoes in mid-summer, when soil temperatures are high and any reduction in soil temperatures is beneficial ([Photo 3.5](#)).

Another family of mulches includes the wavelength-selective mulches, which selectively transmit radiation in some regions of the electromagnetic spectrum but not in others ([Loy et al., 1989](#)). These mulches absorb photosynthetically active radiation and transmit solar infrared radiation, providing a compromise between black and clear mulches. The infrared-transmitting mulches afford the weed control properties of black mulch but are intermediate in terms of increasing soil temperature between black and clear mulch. The color of these mulches can be blue-green or brown. These mulches warm up the soil similar to clear mulch but without the accompanying weed problem.



Photo 3.4 Laying different colored plastic mulches and drip irrigation tape.



Photo 3.5 Applying metallized silver reflective mulch and drip irrigation tape.



Photo 3.6 Staked tomatoes on raised beds covered with red plastic mulch and using drip irrigation.

The next colors to be researched were red, blue, orange-green, and yellow-colored mulches which reflect different radiation patterns into the plant canopy of a crop like tomato, thereby affecting photosynthesis and/or plant morphogenesis and may increase early yields as was the case with red-colored mulch (Decoteau et al., 1988, 1989) (Photo 3.6).

The colors can also affect the behavior of certain insects. Yellow, and to a lesser degree, orange, and green surfaces attract the green peach aphid ([Broadbent, 1948](#)). Mulches with an aluminum or metallized silver surface color have been shown to repel certain aphids and to reduce incidence of aphid-borne virus in summer squash ([George and Kring, 1971](#); [Lamont et al., 1990](#)) ([Photos 3.7 and 3.8](#)).



Photo 3.7 Various colored mulches being tested at Kansas State University.



Photo 3.8 Colored mulches being evaluated at Penn State.

Advantages of Plastic Mulches

Earlier and Higher Overall Yields

Raising the soil temperature promotes faster crop development and earlier yields (Clarkson and Frazier, 1957). Researchers have demonstrated earlier (7–14 days and up to 21 days) and increased yields (normally two to three times that of unmulched soils), depending on geographical location, soil type, plastic mulch used, and crops including: sweet corn and eggplant (Pollack et al., 1969); tomatoes (Bhella, 1986); muskmelons (Schales and Sheldrake, 1966); peppers (Stephenson and Bergman, 1963); cucumbers (Paterson, 1980); summer squash (Bhella and Kwolek, 1984); okra (Brown et al., 1986); and watermelons (Bhella, 1978).

Reduced Evaporation

Because of the high degree of impermeability of plastic mulches to water vapor, evaporative loss of water from the soil is reduced. The use of drip irrigation in conjunction with plastic mulch reduces moisture evaporation from the mulched soil and decreases irrigation requirements (Hanlon and Hochmuth, 1989). This has been related to water savings of 45% compared to overhead sprinkler systems (Clough et al., 1987; Jones et al., 1977).

Fewer Weed Problems

Black, white-on-black, reflective, and wavelength-selective mulches will reduce light penetration in the soil. Weeds generally cannot survive under the mulch. An exception is nut grass, whose nut-like tubers provide enough energy for the seedling to puncture the mulch, emerge and grow. With clear plastic mulch, an herbicide or fumigation will be required to prevent weed growth beneath it.

Reduced Fertilizer Leaching

Excess water runs off the impervious mulch. Fertilizer beneath the mulch is not lost by leaching (Locascio et al., 1985). The plastic mulch aids in retaining nutrients within the root zone, permitting more efficient nutrient utilization by the vegetable crop (Cannington et al., 1975).

Reduced Soil Compaction

Soil under the plastic mulch remains loose, friable, and well-aerated. Roots have access to adequate oxygen, and microbial activity is enhanced ([Hankin et al., 1982](#)).

Root Pruning Eliminated

Except for the area between the mulched beds, cultivation is eliminated therefore, eliminating root pruning of the crop. Weed growth in these areas can be controlled by an approved herbicide.

Cleaner Product

The edible product from a mulched crop is clean and less subject to rots, because soil is not splashed on the plants or fruit. This is accomplished by a raised bed that is firm and tapered away from the row center and plastic mulch that is stretched tight to encourage water runoff.

Gas Exchange

Mulch film is nearly impervious to carbon dioxide released by roots or decomposition of organic matter in the soil and accumulates beneath the plastic mulch ([Sheldrake, 1963](#); [Baron and Gorske, 1981](#)). Because the film does not allow the gas to penetrate, it has to escape through the holes punched for the plants. This creates a “chimney effect,” resulting in higher levels of carbon dioxide for the actively growing leaves near the transplant hole ([Hopen, 1965](#)).

Aids in Fumigation and Soil Solarization

Mulches increase the effectiveness of soil fumigant chemicals. Because of the impervious nature of the plastic mulch, it acts as a barrier preventing gas escape and keeps gaseous fumigants in the soil ([Scoville and Leaman, 1965](#)). Plastic mulches, especially clear, are used in soil solarization to control soil pests ([Stapleton, 1991](#)).

Reduced Drowning of Crops

Water is shed from the row area by the tapered bed; excess water runs off the field, reducing drowning and other excess soil water stress problems.

Ability to Double/Triple Crop

Once the first crop has been harvested, a second crop can be grown on the plastic mulch. This “intensive cropping” produces two or three crops from the annual expenses for plastic mulch and drip irrigation tubing. The second or third crop can be fertilized through the drip irrigation line (“fertigation”) using soluble fertilizers and a fertilizer injector (Clough et al., 1987; Marr and Lamont, 1992).

Disadvantages of Plastic Mulches

Removal and Disposal

A major problem with plastic mulch is its removal from the field after cropping (Stall and Bryan, 1981). Plastics have been disposed of routinely by burning, burial, or dumping in landfills. The growing environmental concerns over disposal of plastic mulches by burning and dumping in landfills have already led to restrictions in some regions (Ennis, 1987) (Photo 3.9).



Photo 3.9 Plastic mulch and drip irrigation tape a disposal problem.

In the early 1960s, photodegradable plastic mulch was recognized as one solution to the disposal problem associated with plastic mulches. Work on biodegradable starch-based film (Otey and Westoff, 1980) and polyolefin polymer and polyethylene copolymer films (Carnell, 1980; Ennis, 1987) has been underway since the 1980s; however, resulting mulches have been quite variable in their rate of degradation (Chu and Matthews, 1984; Wien, 1981).

Newer biodegradable products (such as Optigro (Leco Industries, Inc., Quebec, Canada); Biolan (CT Films, Schaumburg, IL, USA); and Plastigone (Miami, FL, USA)) have shown more satisfactory degradation characteristics when tested in different regions of the country (Clough and Reed, 1989; Sanders et al., 1989; Wolfe, 1989; Kostewicz and Stall, 1989; Johnson, 1989) (Photo 3.10).

Other options to the plastic mulch disposal problem are retrieval and recycling or incineration/energy reclamation for the British Thermal Units (BTUs) locked inside the plastic mulch. This work was pioneered by Jim Garthe, Mike Orzolek, and Bill Lamont at Pennsylvania State University and is still a viable answer to the disposal problem of both agricultural and consumer nonrecyclable plastic mulches.



Photo 3.10 Biolan NT20 Mulch being tested.



Photo 3.11 Waterwheel transplanter for use with plastic mulch systems of production.

One result of the disposal issue surrounding conventional plastic mulches was the advent and testing of the biodegradable plastic mulches which reduce nonrecyclable waste, conserve resources and decrease environmental pollution (Miles et al., 2012). Most biodegradable plastic mulches that are currently available are made from plant starch. The agricultural films made from starch are prepared using conventional plastics processing technology. One problem is the poor mechanical properties of starch which includes its brittleness and as a result it must be blended with other polymers and/or plasticizers. The list of products currently on the market include Biosafe, Eastar Bio, Eco-Flex, Ingeo, Mater-Bi, and Paragon (Hayes et al., 2012).

Greater Initial Cost

The use of plastic mulch will increase the cost of production for a given crop. This is due to investment in some specialized equipment, including a bed press, mulch layer, and mulch transplanter, or plug-mix seeder (Photo 3.11). These costs must be offset by increased income from earlier harvests, higher yields, and better-quality fruit to create an economic advantage for the use of plastic mulch.

Plastic mulches have allowed for greater mechanization and efficiency in the production of selected vegetable crops since the late 1950s and will continue to provide a proven means of modifying the microenvironment around a vegetable crop (Photo 3.12).



Photo 3.12 Muskmelon crop on black plastic mulch with drip irrigation and rye windbreak for wind protection.

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4 Row Covers

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Introduction

One of the simplest forms of protected agriculture is the use of row cover, which is defined by Wells and Loy (1993) as “flexible, transparent material (polyethylene, polyester, or polypropylene) that is hoop-supported or floated over a row or rows of crops at planting (seeds or transplants).” Row cover that is placed directly on top of a growing crop is referred to as floating row cover, or direct cover. Row covers supported by varying types of hoops or frames are often referred to as low tunnels. Size differentiates low from high tunnels, as low tunnels are typically less than 1 m tall and wide.

Initially, the main purpose of using row covers was to enhance growth early and late in the growing season, when outdoor temperatures were low. While this is still the most common use, specialized row covers are used primarily as insect barriers or to provide overwinter protection, and many other functions of row covers have been described, including freeze/frost protection, erosion control, and plant disease reduction.

Espi et al. (2006) reports that the acreage of low tunnels has held constant in most areas worldwide since the early 1990s, but that it has steadily increased in China, which had over 700,000 hectares in low tunnels in 2006. It is unclear whether this figure includes areas under floating row cover, or crops grown under supported row covers made of materials other than polyethylene.

Basic row cover technologies and common uses have been reviewed by Wells and Loy (1985), Wells and Loy (1993), and Jensen and Malter (1994). This chapter will focus primarily on newer research that describes the effects of row covers on crops and the microclimate surrounding crops, as well as on new developments in row cover materials and uses.

Row Cover Materials

Aside from early uses of paper coverings for season extension among celery growers (Wittwer and Castilla, 1995), polyethylene, or clear plastic, was used in the first applications of row cover over crops. Polyethylene sheets require daily ventilation to prevent excessive temperature accumulation, which can cause crop damage (Soltani et al., 1995). Beginning in the early 1980s, slitted and perforated covers whose automatic ventilation reduced daily labor requirements became available (Wells and Loy, 1985). Slitted and perforated polyethylene covers are still commercially available, but these and solid polyethylene covers are now primarily used in applications where crops benefit from as much heat as possible, for a limited time. One example is for the first few weeks of growth for very early plantings of sweet corn in cold climates. In this case, polyethylene row covers are removed from the crop once daytime temperatures reach a certain maximum temperature, before crop damage occurs.

Spunbonded, or nonwoven, fabrics made of polypropylene or polyester are now the materials most commonly used as agricultural row covers. Synthetic agrotexile fabrics, sometimes referred to as “fleeces,” are manufactured in a wide array of weights and thicknesses suited to different purposes. The lightest weight fabrics allow the greatest light transmission and provide a physical barrier to insects, whereas heavier fabrics are more durable and more insulating but allow less light transmission. Weights typically range from 0.45 to 2 oz/yd² or 15–70 g/m². The lighter fabrics permit 70–90% of the light to pass through, and the thickest fabrics, designed for overwintering, may allow as little as 30% of the light to pass through the fabric.

Evans et al. (1997) evaluated fabrics made of wool as alternatives to polyester and polyolefin products; the test products that were evaluated were not sufficiently durable to confer the benefits that the synthetic covers did.

One relatively recent development in row covers is the woven mesh net made of polyethylene or polyamines, such as Proteknet (Dubois Agrinovations, Quebec, Canada), Wondermesh (Wondermesh Ltd., Aberdeenshire, Scotland), or Agronet (Gogo et al., 2014). These nets are produced in a range of mesh sizes and are marketed for the primary purpose of insect exclusion, with limited effects on the crop microclimate. Fig. 4.1 shows a small planting of Brussels sprouts covered with Proteknet for insect exclusion during the warm summer growing season.



Figure 4.1 Brussels sprouts covered with Proteknet to exclude various insects during production.

As with other agricultural plastics, disposal of row covers remains a challenge with the use of this technology. Biodegradable nonwoven fabric row covers such as Bionolle and IBWCH (Siwek et al., 2012, 2013) are currently the focus of research and development; these products are not yet widely commercially available.

Effects of Row Covers on the Crop Microclimate

Row covering materials affect the crop microclimate in a number of ways. Specific effects vary and depend on many factors including the type of fabric used (light transmission, weight, or material), weather conditions at the time of use, and whether or not the cover is supported.

Temperature

Several researchers have documented elevated air and soil temperatures in the crop zone under row covers (Wells and Loy, 1985; Soltani et al., 1995). Enhanced growth under row covers has been shown to have a direct relationship with growing degree-days measured, suggesting that higher air temperatures are most directly related to growth (Wolfe et al., 1989; Albright et al., 1989; Soltani et al., 1995). Excessive temperatures under row covers have been shown to negatively impact some crops, such as tomato, which experiences reduced flower set at temperatures greater than 30°C.

The increase in temperatures conferred by row covers is greatest in the daytime; temperatures fall quickly at night. Wells and Loy (1985)

report that polyester covers confer frost protection of 1–2°C frost protection, compared with 2–3°C for polypropylene covers. In some cases, however, significant frost protection has been observed. For example, [Arancibia and Motsenbocker \(2008\)](#) showed that temperatures under spunbonded row cover were approximately 7.5°F warmer under cover than outdoors. At temperatures above freezing, the minimum daily temperature under row cover is very similar to outdoor temperatures, and temperature is occasionally lower under row covers than outdoors. [Sideman et al. \(2012\)](#) showed that the difference between minimum low tunnel and outdoor temperatures increases in a linear fashion when outdoor temperatures fall well below freezing.

[Giminez et al. \(2002\)](#) monitored air and soil temperature in several different crops grown under row covers and outdoors. They found that, while air and soil temperatures were usually higher under row cover than outdoors, there were circumstances where the reverse was true, particularly for Chinese cabbage, late in the cropping cycle. The authors hypothesized that this was due to the use of a significant portion of the net energy by transpiration in the relatively large crop biomass, resulting in a temperature decrease.

Light

Light transmission varies for different commercial row covers, with most lightweight nonwoven materials reportedly transmitting approximately 70–90% of the incident light. Values reported by manufacturers are maximum light transmission values; in practice, other factors such as dust accumulation on the exterior surface and condensation on the interior surface of the cover reduce the photosynthetic photon flux density (PPFD). [Giminez et al. \(2002\)](#) found that actual PPFD under cover ranged from 85% to 65% for a cover whose theoretical maximum light transmission was 90%.

Relative Humidity and Vapor Pressure Deficit

When [Wells and Loy \(1985\)](#) reviewed the use of row covers in agriculture, humidity and air movement within the low tunnel microclimate had been little studied. Since that time, some researchers have documented higher relative humidity under row covers than in uncovered crops ([Hernandez et al., 2010](#); [Moreno et al., 2003](#)). In contrast, however, [Nair and Ngouajio \(2010\)](#) found that relative humidity under hoop-supported covers of varying weights (17 and 40 g/m²) was lower

than that measured outdoors. They hypothesized that higher temperatures within the low tunnels increased the vapor pressure deficit, reducing relative humidity.

Airflow

Wells and Loy (1993) proposed that a reduction in wind exposure is one of the factors involved in improved growth of plants under row covers. Mermier et al. (1995) measured ten times less airflow in low tunnels as compared with uncovered plants. They found that this reduction in airflow limited gas exchange in the plant canopy and that the low tunnel microclimate had higher relative humidity than was measured among uncovered plants. In wind tunnel experiments in which airflow was measured around simulated plant canopies with and without row covers, Mao and Kurata (1997) also found that row covers greatly suppressed turbulent diffusion, or air movement, within the plant canopy and found greater suppression with less porous cover. Nair and Ngouajio (2010) observed higher temperatures under heavier weight compared with lighter weight row covers, despite reduced light transmission through these covers, and suggested that reduced air movement inside row-covered low tunnels was responsible. To our knowledge, studies of airflow underneath floating row covers that are in direct contact with some part of the crop canopy and that have sufficient slack to move in windy conditions have not been conducted.

Effects of Row Covers on Crops

Season Extension and Yield Increases

One of the primary uses for row covers is to extend the growing season. Fig. 4.2 shows large sheets of floating row cover installed over mixed vegetables to promote early season growth. Many researchers have demonstrated that crops grown under row covers can be harvested earlier than those in open field. For example, for head lettuce, Jenni et al. (2003) found that row-covered low tunnels advanced maturity by 1–4 days with no mulch (e.g. bare soil), but that, when used with infrared-transmitting mulch, the low tunnels advanced maturity by 10 days over uncovered plants. Similarly, Arancibia and Motsenbocker (2008) found that row covers increased early yield of seedless watermelon as compared with open-field production.



Figure 4.2 Row covers installed over mixed vegetables in early spring to enhance early season growth. Photo credit: Eric Sideman.

Total marketable increases have also been documented with the use of row covers. For example, marketable yields of cucumber, watermelon, and French beans were documented under row covers as compared with open-field production ([Nair and Ngouajio, 2010](#); [Soltani et al., 1995](#); [Gogo et al., 2014](#)).

Increasingly, row covers are also used to extend the growing season into the fall, in regions with short growing seasons. [Fig. 4.3](#) shows late fall harvest of kale that has been protected through several frosts by row covers. Leaf quality is enhanced under the row cover, permitting harvest of high-quality salad greens later into the fall than would be possible without the cover.

Insect Pests

Row covers are frequently used to manage insect pests, primarily serving as a physical barrier. In addition to direct crop pests, vectors of virus diseases may also be excluded with the use of row covers. The use of row covers as an insect control strategy is compatible with organic or no-spray production systems, and they are widely used among organic growers in the Northeastern United States.

Many researchers have demonstrated that row covers can be used to exclude insect pests from a wide assortment of crop species ([Perring et al., 1989](#); [Costa et al., 1994](#); [Arancibia, 2007](#); [Rojas et al., 2011](#)). For example, [Jenni et al. \(2003\)](#) found that low tunnels covered with lightweight, spunbonded fabric reduced early season aphid infestation in



Figure 4.3 Fall harvest of high-quality kale leaves protected under row cover. Photo credit: Ruth Hazzard.

head lettuce. In carrot, [Rekika et al. \(2008\)](#) found that the use of floating row cover for a period of 35 days after seeding reduced carrot weevil damage by 65–75%.

While row covers exclude pests coming from outside the crop planting, they do not exclude pests that already are present inside the crop planting when the row cover is applied. To obtain good control of pests that overwinter in crop debris and soil, it is therefore critical to couple the use of row covers with crop rotation. The warmer temperatures under row covers, particularly in early spring and late fall, provide a favorable environment for insect reproduction as well as crop growth. Growers using row covers for fall season extension for hardy greens have reported significant aphid populations on weed or crop species under row covers.

Woven polyethylene net materials have recently become commercially available, and the primary use of these nets is insect control. Mesh dimensions vary depending on the intended organisms to exclude, with the smallest mesh sizes small enough to exclude thrips. While comparatively more expensive, nets are durable and therefore have a longer useful life than lightweight nonwoven materials. Small-scale growers in New England are using nets for insect control in vegetable crops, and some are experimenting with finer mesh nets to exclude pests of berry crops such as spotted wing drosophila.

Greater increases in air temperature have been observed with finer mesh or pore size, such that daytime temperatures are lower when using woven nets with coarser mesh than when using finer mesh or nonwoven row cover (Saidi et al., 2013). As a result, nets may be well suited for insect protection in tropical climates or for production of cool-season crops in warm seasons of temperature climates. For example, growers in the Northeastern United States use nets to protect brassica crops from flea beetles and lepidopteran pests throughout the warm summer months.

Insecticide-treated nets, which are widely used for mosquito control as bed nets, have been used for crop protection in tropical areas (Martin et al., 2006, 2013; Gogo et al., 2014). In some cases (Martin et al., 2006, 2013), insecticide-treated nets resulted in lower levels of insect pests compared with untreated nets; in other cases (Gogo et al., 2014), treated and untreated nets performed similarly.

Beneficial Insect Populations

In addition to excluding crop pests, nonwoven row covers and insect netting also exclude beneficial insects, including predators, parasitoids, and pollinators, from crops. For example, Martin et al. (2013) found that netting was an effective barrier to parasitoids as well as insect pests in cabbage, finding very low percentages of parasitized aphids under netting compared with uncovered treatments.

Cucurbit crops (melons, squashes, pumpkins, and cucumbers) are host to many severe pests that can greatly reduce yields or cause mortality, if not controlled, including striped and spotted cucumber beetle, squash bug, and squash vine borer. While these pests can successfully be excluded through the use of row covers, the critical nature of pollination for fruit development makes row cover use practical only if removed at flowering. This limits the utility of row covers for the insect pests that are prevalent later in the season, such as squash bug and squash vine borer. Recent research has revealed potential strategies to permit pollination while maintaining pest protection after flowering. Vaissière and Froissart (1996) demonstrated that two strategies had the potential to improve pollination in cantaloupe, while still offering the benefits of row covers. One strategy involved opening the ends of row covers to permit colonization by pollinators and the other involved introducing a multiple entrance hive of honeybees (*Apis mellifera adansonii* Latreille) at the ends of covered rows. Further, Minter and Bessin (2014) explored different techniques to naturally or artificially

introduce native pollinators that specialize in cucurbit crops. They found that either introducing *Peponapis pruinosa* Say (the squash bee) underneath floating row covers or removing the row covers at night to permit natural colonization of squash bee resulted in fruit set and marketable yields comparable to the uncovered treatments. At the same time, damage from squash bug and squash vine borer, as well as sunscald, were reduced due to the presence of the row cover.

Crop Quality

In comparison with crop yields and microclimate effects of row covers, relatively few researchers have investigated the effects of row covers on crop quality. Of those that did, [Saidi et al. \(2013\)](#) found that the use of agricultural nets as row covers over tomato in Kenya resulted in firmer fruits with higher soluble solids and lower titratable acidity than open-field grown tomato, as well as producing higher yields. [Gogo et al. \(2014\)](#) found that net-covered French bean pods were of higher quality, with longer and thicker pods, than uncovered French beans. [Giminez et al. \(2002\)](#) found that the crop quality of greens (cabbage, lettuce, and spinach) grown under floating row cover in Spain was higher than that for uncovered crops, because the covered leaves were thinner and more tender, which the authors concluded resulted in a higher value product. [Igarashi et al. \(2001\)](#) reported slightly lower levels of sugar and nitrogen contents in leaves of komatsuna grown under a novel row cover film that consisted of spunbonded polyester nonwoven fabric combined with polyethylene flat checker-patterned yarn. [Hernandez et al. \(2010\)](#) found that row covers improved quality of Chinese cabbage by reducing the incidence of tipburn and bolting and by improving head formation.

A specialized application of row cover resulted in significant differences in crop quality for asparagus. [Makus and Gonzales \(1991\)](#) demonstrated that opaque plastic covers supported by hoops successfully permitted the production of white asparagus with less labor than the traditional method of burying in soil. The opaque plastic they used was white on one side and black on the other side. Minor differences were detected depending on which color was on the exterior, but coverings in either orientation produced white spears with higher soluble solid content than uncovered green spears. An additional benefit was some freeze protection; several hours' exposure to temperatures below freezing resulted in significantly less damage to spears under plastic compare with uncovered spears.

Overwintering

In cold climate regions, temperatures below freezing limit plant growth during much of the year. In recent years, row covers have been used to reduce winter freeze injury to perennial fruit crops as well as hardy vegetable crops.

Strawberry

Straw mulch is traditionally used for strawberry winter protection in cold climates of the Northern United States, to prevent frost heaving and to protect plant crowns from freezing in snowless winters. Because it is impermeable to light, straw is raked off plants as early in the spring as is practical. Row covers have been used as an alternative to straw mulch (Gent, 1990; Bushway and Pritts, 2002; Pollard and Cundari, 1988). In addition to protecting plants from winter injury, spunbonded row covers have been shown to increase yields over straw-mulched plants and to promote earlier flowering and fruit development in some studies (Pollard and Cundari, 1988; Gent, 1990). Application of polypropylene row cover early in the spring enhanced total fruit yield, possibly because of enhanced photosynthetic rate and starch accumulation in leaves (Bushway and Pritts, 2002; Gent, 1990). Similarly, fall-applied row cover increased marketable yield in strawberry, presumably because it permitted additional late-season growth (Fernandez, 2001). Row covers have also been successfully used for early spring frost protection of strawberry (Hochmuth et al., 1993; Poling et al., 1991). According to Poling et al. (1991), a range of materials tested provided varying degrees of frost protection, resulting in blossom temperatures that were higher than the control by 0.4–1.2°C.

Blackberry

Lack of winter hardiness among blackberry varieties currently limits blackberry production in colder regions. Most commercial varieties are not adapted to areas where winter temperatures fall below -13°F (-25°C), and winter injury has been documented at temperatures much warmer than these lower limits (Takeda et al., 2008). Winter covering with a heavyweight row cover (1.5 oz/yd²), in combination with a trellising system that allows canes to be moved close to the ground, resulted in less cane injury, increased flower production, and increased

yields in trailing blackberry in West Virginia, U.S. Department of Agriculture (USDA) Plant Hardiness Zone 6b (Takeda et al., 2008; Takeda and Phillips, 2011). A similar reduction in winter injury and increased fruitfulness has been observed in New Hampshire with untrellised upright thornless blackberries covered with a very heavy (6 oz/yd²) winter protection fabric (Sideman, unpublished results).

Winter Vegetable Production

In the Northeastern United States, it is now common for vegetable growers in USDA Hardiness Zones as cold as zones 4–6 to combine season extension techniques to enable winter production of hardy salad greens in a climate that is well below freezing, often snow-bound, and that seems inhospitable to growing plants. Eliot Coleman, a Maine farmer and innovator, pioneered work in this area. His extensive on-farm experimentation and studies of season extension techniques in Europe led him to conclude that the use of small tunnels within larger tunnels offered much greater temperature protection than either alone would provide. He published his observations in organic gardening books and grower manuals (Coleman, 1998, 1999, 2009). While there are few reports of the use of tunnels within tunnels in very cold winter climates in the peer-reviewed literature, the use of supplemental row covers within unheated high tunnels to permit production of cold-hardy crops (e.g., spinach, claytonia, mache, kale, and others) throughout the winter is widely used among farmers in cold climates.

Bumgarner et al. (2011) showed that small tunnels constructed of slitted polyethylene, inside of unheated high tunnels, increased biomass and yield of lettuce during cool spring and fall seasons in Ohio (USDA Hardiness Zone 6a, minimum temperatures of -10°F to -5°F). Martin and Sideman (2012) investigated the use of heavy (1.25 oz/yd²) polypropylene row cover to create low tunnels within a high tunnel to protect fall-planted winter sprouting broccoli in New Hampshire (USDA Hardiness Zone 5b). They found that overwinter survival, early harvest, and total yields of the spring-harvested broccoli were all higher for plants grown under supplemental row cover within the unheated high tunnel. At the coldest parts of the winters, low tunnels within high tunnels were much warmer than high tunnels alone, with minimum temperatures $8.4\text{--}11.5^{\circ}\text{C}$ higher than temperatures in the unheated high tunnel and $8.9\text{--}16.9^{\circ}\text{C}$ warmer than outdoor temperatures.

Overwintering Vegetables

Low tunnels have been used to overwinter cold-tolerant vegetable crops in cold climates. In low tunnels, frozen ground limits access to the crop for several months over the winter, so crops are planted in fall and harvested in early spring. [Sideman et al. \(2012\)](#) investigated temperature fluctuations during the winter in a range of sites in Northern New England under several different covering materials and combinations of materials. Of the treatments that they evaluated, they found that the combination of heavy polypropylene cover (1.25 oz/yd^2) with 6 mil greenhouse polyethylene resulted in the greatest temperature difference and crop survival between low tunnel and outdoor temperatures, with low tunnels experiencing $20\text{--}40^\circ\text{F}$ warmer than outdoor temperatures at the coldest parts of the winter. The temperature moderating effects of the low tunnels were greatest at the coldest outdoor temperatures. [Fig. 4.4](#) shows low tunnels set up for overwintering in New Hampshire. In subsequent studies, low tunnels permitted overwinter survival of several vegetable crops including kale, spinach, and mustard greens for spring harvest (Sideman, unpublished results).

Both [Coolong and Williams \(2014\)](#) and [Sideman et al. \(2014\)](#) used hoop-supported row covers to protect fall-planted onions in Kentucky and New Hampshire. [Sideman et al. \(2014\)](#) found that the combination of heavy polypropylene cover (1.25 oz/yd^2) with 6 mil greenhouse polyethylene increased onion survival as compared with no row cover, and Coolong and Williams found that a single layer of heavy polypropylene (1.5 oz/yd^2) increased survival and yields compared with straw mulch.



Figure 4.4 Low tunnels constructed of 1.25 ounce per square yard row cover, covered with 6 mil polyethylene, set up to protect hardy vegetable crops over winter in New Hampshire, USA.

In Poland, nonsupported row covers are frequently used for winter protection of fall-planted onion (Siwek et al., 2013). Siwek et al. (2013) evaluated two weights of each of the two new biodegradable nonwoven materials, compared with standard nonwoven polypropylene covers, placed directly on top of fall-planted onions in Poland. They found inconsistent results between years but that the biodegradable and standard polypropylene covers did increase survival and yields in one of the 3 years.

Container-Grown Nursery Stock

Researchers have investigated the use of unsupported row cover materials as part of winter protection systems for container-grown nursery stock. Regan et al. (1989) found that nonwoven fabrics (1.25 and 1.9 oz/yd²) did not protect a range of ornamental species grown in containers from winter injury. They did, however, find that a commercial insulated foam product (Microfoam, Ametek, Inc., New York, NY) did reduce winter injury in container-grown plants when winter low temperatures reached -18°F . Pellett et al. (1985) found similar results for Microfoam and Polyfoam (Guilford Packaging and Fiber, Inc., High Point, NC, USA) at even colder temperatures, finding that both covers reduced winter injury for several of the species investigated. The limited research suggests that fabrics that provide sufficient protection for plants grown in ground are not necessarily sufficient to protect container-grown plants. This is likely because roots are considerably less tolerant of cold damage than shoots of plants, and they do not become fully dormant. Roots deacclimate easily, so cold damage can occur anytime throughout the year (Green and Fuchigami, 1985; Mathers, 2003). Due to the expense and inconsistent protection offered by covering fabrics, other systems, such as pot-in-pot or fiber pot production systems, and the use of polytunnel structures, are much more commonly used in the nursery industry than row cover foams or fabrics for overwintering (Mathers, 2003).

Similarly, row cover fabrics were evaluated by Dionne et al. (1999) for the protection of turf in golf courses. They found that permeable and impermeable covers alone, without snow cover, did not provide significant soil insulation. When combined with insulating materials such as air space or straw, however, they did reduce temperature fluctuation and enhanced winter survival of golf greens.

Summary

While season extension remains a common use for row covers in agriculture, row covers are also commonly used as insect barriers to improve yields or crop quality and for winter freeze or frost protection. Effects of row covers on crop microclimate variables such as temperature, light, relative humidity, and airflow vary with specific materials, crops, and growing seasons. While nonwoven polypropylene and polyethylene are still widely used, new developments in row covers include woven mesh nets with the primary purpose of insect exclusion and biodegradable nonwoven fabric covers.

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5 Drip Irrigation

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Introduction

Water is important for optimal vegetable production, not only for total yield but also for high-quality produce. For example, adequate water is needed to produce high yields of large pepper fruits with thick walls, desirable in the marketplace. Agriculture uses a considerable portion of the available fresh water on the globe and as the need for food grows with the growth in population, so will the demand for water. Some estimates are that, on average, about 70% of the global freshwater supplies are committed to agriculture. This number is nearly halved for the United States due to increased water-use efficiency related to farmer adoption of irrigation technologies like drip irrigation. Farmers are keenly aware of the current and future competition for available water and they are interested in adopting the most efficient irrigation systems available. The most common irrigation systems used for vegetable production in the United States are sprinkler, subirrigation, and drip irrigation. This chapter covers drip irrigation, especially in conjunction with plastic-mulched vegetable production systems.

What Is Drip Irrigation

Drip irrigation is a crop water-supplying system consisting of thin-walled plastic tubing placed on or in the soil along the rows of plants to supply water (and nutrients) to crops during the growing season (Fig. 5.1). Other terms for drip irrigation sometimes include microirrigation or trickle irrigation. Some scientists consider microirrigation a more general term to include highly efficient irrigation systems, such as microsprinklers or microjets, along with drip irrigation. For the purposes of this discussion, drip irrigation is considered to be a type of microirrigation involving the application (dripping) of water from emitters directly to the soil along the row of plants in a field via plastic



Figure 5.1 Drip-irrigation tubing placed between rows of onions. Photo courtesy from Ron Goldy. Available from: http://msue.anr.msu.edu/news/irrigation_and_disease_development_in_michigan_vegetables.

tubing. Drip irrigation, when properly managed, offers increased efficiency of water application, resulting in less water usage for crop production compared with other irrigation systems, such as subsurface or sprinkler systems. Drip irrigation can have irrigation efficiencies of 90–95% compared with sprinkler systems of 75–85%. This means that 90–95% of the water drawn from a source reaches the crop root zone. Some of the increased efficiency comes from reduced evaporation of applied water because the water is applied directly to the soil and often under polyethylene mulch. Societal, environmental, and economic demands for water efficiency on the farm have led to widespread adoption of drip irrigation in agriculture, particularly for high-value crops such as vegetables and fruits. Drip irrigation also operates under lower pressure compared to sprinkler systems, so less energy is required for irrigation with drip systems. While the polyethylene tubing is usually replaced each season, adding costs to the annual crop budget, these investments are typically minimal. More information on the benefits and challenges with drip irrigation are presented below.

Origins of Drip Irrigation

Ancient farmers devised technologies to water plants efficiently, knowing that crops needed water when rainfall was not adequate. Powerful pumps and pipes were not available as today to move water long distances from source to crop. One ancient irrigation approach was

a clay pot, filled with water, placed in the ground near crop plants (Bainbridge, 2001). Water in the clay pot seeped through the clay walls or holes in the walls to water plants and the rate of release was related to the soil moisture, which was related to crop water use. As the soil dried out, more water moved through the pot wall to replace the lost water in the soil. In the mid-1800s, clay pipes were used for irrigation (and drainage) in Afghanistan. Perforated clay or metal pipes were used in Germany to apply water to crops in the 1920s. The idea to bring water to plants through plastic tubes may have originated in Australia by an inventor Hannis Thill. World War II ushered in the era of plastics and soon water was being applied to crops through polyethylene tubes (“spaghetti tubes”) and powered pumps helped move water long distances, sometimes from underground, to the crop or greenhouse. The idea of drip irrigation in the United States traces back to the 1950s with work by a company (Chapin Watermatics) working with greenhouse plants in New York (Bucks, 1995; Lamm et al., 2007). In the late 1950s and early 1960s, an Israeli company (Netafim) worked on new technologies to distribute water more efficiently from plastic tubes, introducing new emitter technology with a labyrinth design. Research and demonstration efforts by university and commercial irrigation personnel, especially in Israel, California, and New York, led to commercial-scale use of drip irrigation for fruits and vegetables (Gustafson, 1979). The first farm demonstration of surface drip irrigation and plastic mulch was conducted with muskmelon in 1963 on Long Island, New York, USA, by Nassau County agent Norm Smith and Richard Chapin (Lamm et al., 2007).

Early drip irrigation systems consisted of polyethylene tubing (e.g., spaghetti tubing) to convey water from a source to the plant. The addition of the emitter to the tubing began to solve irrigation uniformity and clogging issues. The plastic-molded emitters provided a labyrinth through which the water passed. In the labyrinth, water velocity was slowed so it could drip from the emitter to the soil rather than run out in a stream. Also, the slowing of the velocity allowed particulate matter to settle and not clog the emitter. One of the biggest benefits from the new emitter technology was the uniformity of water application down a length of crop row. Uniformity is critical for efficient fertilizer solution delivery through the irrigation tubing. Various kinds of drip tubing have been developed since the 1960s. Some tubing consists of a thick wall and is more or less rigid with emitters placed at strategic distances along the tubing. This tubing is more durable and can be used for several to many seasons before being discarded or recycled. Thinner-walled tubing, sometimes called drip tape, achieves the same goals of uniform delivery of water through emitters but has a shorter lifespan for

field use. It is not the purpose of this chapter to discuss all the various brands of drip tubing and tape; suffice it to say, there are many products on the market, each with its own patented tube design, emitter system, and market target. Some products are designed for long-term crops like tree fruits, whereas other products are designed for vegetables, cotton, or other short-season crops.

Uses of Drip Irrigation

There are two general applications of drip irrigation for crop production—surface drip and subsurface drip. With surface drip irrigation, the tubing or tape is placed on the surface of the soil, in a groove in the soil, or just below the soil surface (Fig. 5.2). Placing the tubing just under the soil, compared with surface placement, reduces the lateral movement (sometimes called “snaking”) of the tubing or tape due to fluctuations in temperature (expansion and contracting of the plastic) or movement due to wind. Surface drip is often used with polyethylene mulch production systems (Fig. 5.3). With surface drip irrigation the water (and nutrients) are emitted from the tubing at or near the soil surface and move laterally and vertically in the soil. Movement of water is facilitated in finer-textured soils or beds than have been mechanically compacted by shaping and pressing. With subsurface drip irrigation, the tubing, usually thicker-walled tubing, is buried in the soil at a depth below tillage equipment. The idea behind subsurface drip system is that the irrigation installations will be more permanent. Subsurface drip systems are more efficient with finer soil texture so that the upward



Figure 5.2 Placing the drip tape in grooves in the center of the bed, then covering with polyethylene mulch for muskmelon. Water moves laterally and vertically from the drip tube. Photo courtesy from George Hochmuth.



Figure 5.3 Drip tape being applied simultaneously with plastic mulch application in Florida. Note the rolls of drip tubing mounted above the mulch applicator. The tubing is fed through a metal tube to the ground and into a shallow notch made in the bed soil. The press pan shapes and firms the bed covering the drip tubing in one pass. Photo courtesy from George Hochmuth.

movement of water by capillarity is assured. Surface drip irrigation can be used with any soil texture from sands to clays and the movement of water is laterally and downward. Drip irrigation was developed to apply water to crops and can be used to apply nutrients and other chemicals to crops. Applying fertilizers through the drip irrigation systems facilitates efficient nutrient management because the fertilizers can be applied near the root system and in small, frequent application throughout the growing season.

Advantages of Drip Irrigation

Drip irrigation has many positive attributes, some of which are advantages over other irrigation systems such as subirrigation or sprinkler irrigation, most importantly in the area of increased irrigation efficiency. Some of the advantages of drip irrigation are:

1. **Reduced water use.** Water is applied near the plant's root system from the drip tubing placed along the row. Other irrigation systems, such as sprinkler, wet the entire soil surface, including the noncrop area between the rows of plants. With this increased efficiency comes lower pumping costs. Drip systems can apply water to similar cropped

areas compared with sprinkler systems with smaller pumps and less energy is used.

2. Potential to apply soluble fertilizers through the drip irrigation system. With the increased water efficiency more efficient fertilizer application can be achieved. Increasing the nutrient application efficiency reduces fertilizer costs and could lead to lesser need for fertilizers, in turn, reducing the potential negative impact on the environment when fertilizers are lost from the soil.
3. Automation. Drip systems can be highly automated. Computers can control the off/on cycling of the irrigation system reducing farm labor needed to operate an irrigation system. Automation can control which areas (zones) of a field are receiving water. Automation can help make efficient fertilizer applications. With automation the farmer can have records of water and fertilizer use, helping evaluate and control costs. There are smartphone apps that enable farmers to closely manage automated drip irrigation systems, often from a distance.
4. Reduce soil erosion. Soil erosion can be reduced, especially when drip irrigation is used with plastic-mulched beds.
5. Uninterrupted usage. Crop harvesting and other field activities can proceed uninterrupted while irrigating the crop.
6. Adaptation. Drip systems can be adapted to small fields, to irregularly shaped fields, and to fields of variable topography. Also, because of the ability to automate the irrigation run times for certain zones, drip allows a farmer to grow crops of differing water needs in close proximity.
7. Potential to reduce foliar disease problems. With drip irrigation the upper stems and leaves of the plant are not wetted, as with sprinkler irrigation. Keeping the leaves dry reduces the chances for disease development.
8. Reduced weed problems. Weed problems are reduced, especially in the interrow spaces because they are not wetted as with sprinkler irrigation. Keeping the soil dry reduces the germination of weed seeds.
9. Ease of double-cropping. Double-cropping could be done easily, when the drip tape and plastic mulch can be used a second time. Additional fertilizer can be added through the drip system for the second crop.

Disadvantages of Drip Irrigation

While drip irrigation has some distinct advantages, there are some challenges with drip systems.

1. Drip irrigation can represent a significant investment for the components, especially if fertilizer injection is contemplated and the system is automated. There are capital investments as well as annual costs. The drip tubing and some additional parts must be replaced each season or after a few seasons of repeated use.
2. Drip systems will require some capital investment for clogging prevention, involving a filtration or water treatment system. The degree of expense will depend on the quality of the source water and on whether fertilizers are to be injected into the system.
3. The drip tubing or tape will need to be replaced, often after each crop/season. There will be expenses associated with the removal of the tubing from the field and its disposal. Landfill disposal often involves a fee. Some plastics can be recycled.
4. Frost protection achievable with sprinkler irrigation is not possible with drip irrigation.
5. Maintenance issues may include rodent and bird damage to drip tape, and anticlogging practices will be needed. The system may need increased attention to flushing to reduce clogging potential.
6. Drip irrigation offers considerable advantages for increasing the efficiency of water and fertilizer use on the farm, but this advantage depends on the grower's efforts at learning how to take advantage of these benefits. Fortunately, there is a wealthy knowledge base in the university Extension system, the irrigation industry, and private consultants. There is considerable information on the internet that must be evaluated carefully for its applicability to one's own farming situation.

Installation of Drip Irrigation Systems

Drip irrigation systems are flexible for various field layouts, depending on the crop system used. The general layout ([Table 5.1](#) and

Table 5.1 Components of a Drip Irrigation System

Major Component	Parts
Water source	Well, surface water body, main line to field, pump
Filters	Media, screen, disc
Chemical injection	Injector system, chemical tank, pressure differential injector, positive displacement, water-drive pump
Controller	Manual (valves), timer, programmable controller, computer
Backflow system	Check valve, low-pressure drain, interlock on fertilizer injection pump
Drip tape	Connectors to lay-flat pipe, flush caps
Other	Pressure regulators, pressure gauges

Fig. 5.4) can be adapted to many cropping systems but presents the main components of most drip irrigation systems. Specific arrangements may differ somewhat from installation specialist to specialist. In typical layouts, there will be a main line delivering water from the pump to the field. The water may be supplied to a pressure tank for smaller farms so the water is readily supplied when the system is turned on. The main line may be a permanently buried polyvinyl chloride pipe with risers strategically placed in the field or along the edge of the field, especially where fields are subdivided into zones. Submains can be connected to the risers and then cross the field to deliver water to the zones. These lines may be flexible or collapsible pipes sometimes called “lay-flat” that can intersect drive roads. Drip tubing or drip tape is connected to these submain pipes by a plastic connector, or a smaller-diameter “spaghetti”-type tubing. Each of these connections may be fitted with a ball valve or other shut-off device so that water delivery to individual rows may be shut off. This is an alternate means to achieve zoning for a small farm or garden. Otherwise, there will be a valve controlling water flow to an entire zone having numerous crop rows. There will be a pressure regulator installed as close to the irrigation zone as possible to maintain the manufacturer’s safe operating pressure for the drip tape. Fields may be laid out in zones, sized so that the manufacturer’s suggested tubing flow rate is maintained. This means that length of row is important and total length of drip tape is important in a zone so that flow from the drip tape emitters is uniform in the zone. Numbers of zones that can be irrigated simultaneously depend on the flow of water

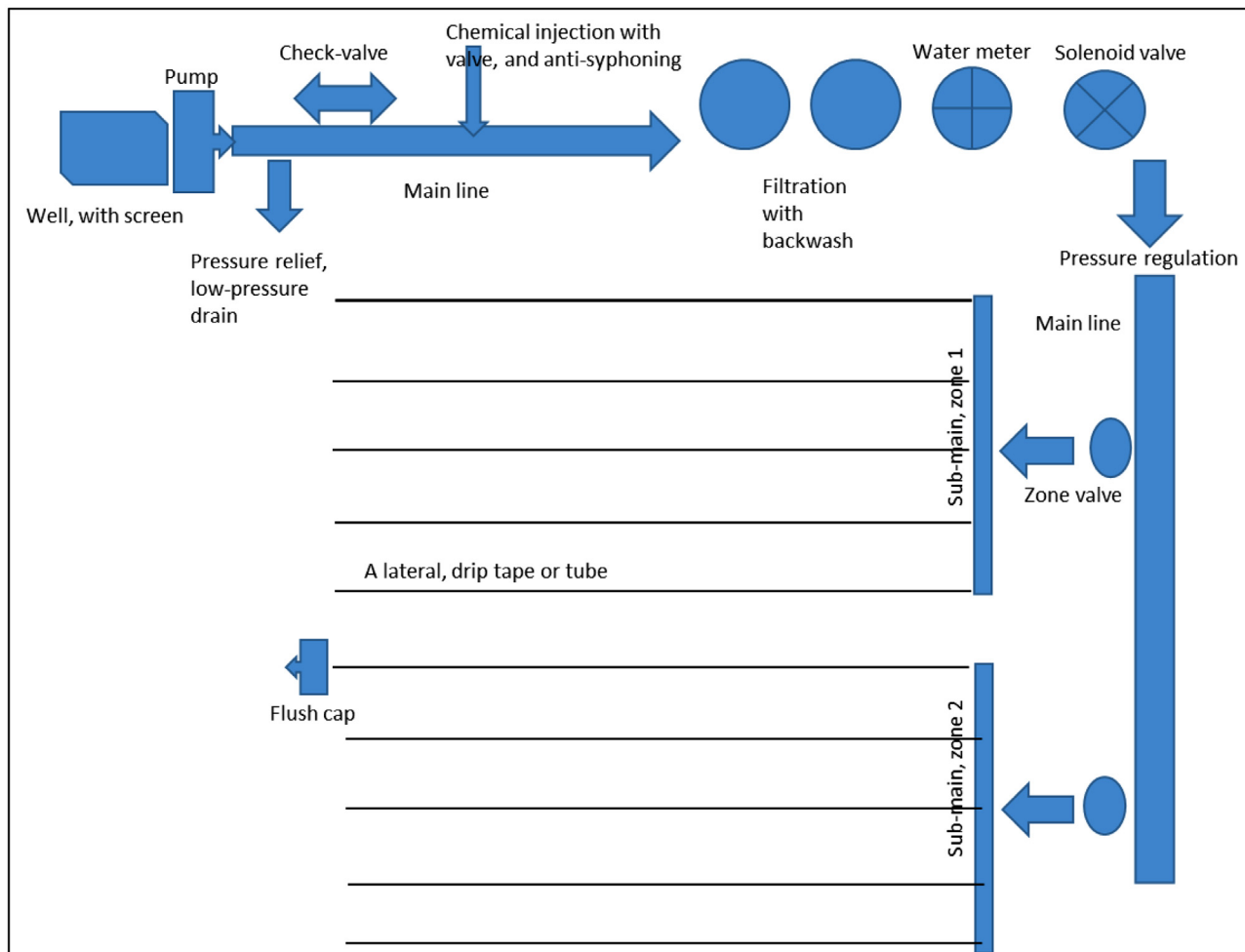


Figure 5.4 Components and general layout of a drip irrigation system. Courtesy from George Hochmuth.

from the pump. Designing the drip system properly is important to avoid problems with flow rate and delivery uniformity. It is best to recommend to farmers new to drip irrigation to develop a cropping plan (types of crops and amounts of each crop) and irrigation needs before the well is drilled and the main lines are installed. The system should be designed to account for any future changes or expansion. More information on drip irrigation design can be found in [Lamm et al. \(2007\)](#) and the many guides available from a state's Extension Service. Qualified drip irrigation installation companies should be consulted about the installation of a drip irrigation system. Time spent in planning will reduce the chances of problems later on with the irrigation system operation and management.

Drip Tubing and Tape

Most specialists use the terms tubing and tape almost interchangeable. For the purposes of this discussion, drip tubing refers to heavier-walled polyethylene tubing, typically with inline emitters ([Fig. 5.5](#)). The tubing wall may be 12–20 mils (1 mil = 1/1000 in. or 0.0254 mm), nearly rigid. Tubing is often used with more permanent crops like fruit crops or where several successive vegetable crops will be grown on the same bed. Drip tape refers to the thinner-walled tubing with various inline emitters ([Figs. 5.5 and 5.6](#)). The tape walls may be 4–12 mil in thickness and are designed to serve for one or may be two seasons. Often tape is referred to as tubing but rarely is tubing also referred to as tape. Tape will be less expensive than tubing in most cases. Tubing will be less susceptible to physical or varmint damage. Tubing and tape are supplied to the farmer on roles from which the tape or tubing is dispensed during field application.

Emitters

There are two general categories of emitters: online and inline emitters ([Fig. 5.6](#)). Online emitters are used more often with more permanent installations such as fruit crops or nursery crops. Inline emitters may be found in semipermanent installations for fruit crops or for sub-surface drip systems. They are also the emitter of choice for most vegetable crop uses. Emitters range in characteristics pertaining to emitter construction, often having tortuous pathways to slow down water and help remove particulate matter, preventing clogging. Emitters may be pressure-compensating so the flow readily adjusts to maintain



Figure 5.5 Types of drip irrigation tubing and tape with emitter spacing. Available from: http://agrilifenews.tamu.edu/media.php?id=1518&KeepThis=true&TB_iframe=true&height=400&width=600.



Figure 5.6 Online (left) and inline (right) emitters. Available from: http://www.irrigationglobal.com/contents/en-us/d296_Drip_Emitters_Definition.html.

uniformity based on the conditions in the field. These emitters are useful in fields with variable topography, helping maintain uniformity of water emission under variable topography down a row.

Emitters for tape may have flow rates ranging from 0.1 to 0.6 gal./min./100 ft. Low-flow rates can increase the size of area irrigated with a certain water delivery rate and can be placed close together along the tubing, but low-flow emitters generally have smaller orifices, so clogging may be an increased concern. Some brands of emitters are designed to physically ward-off root intrusion. Roots may be encouraged to enter emitters when irrigation amounts are not optimum.

Growers considering tubing, tape, and emitter types should think about the following aspects of the product they may use (Table 5.2). Irrigation suppliers and specialists can help sort out all the variations among products to determine the best product for the particular cropping situation.

Tubing Placement in the Row

There are various means for drip tubing or tape placement in the field. Generally, there will be one tube per row of crop. Sometimes one tube will supply water for two rows of crops such as for twin-row pepper or strawberry, where two rows of crop are grown close together on one bed. For tomato or watermelon there will be one row of crop and one tube per bed. Drip irrigation works especially well with plastic-mulched crops but can be used with unmulched crops. With unmulched

Table 5.2 List of Considerations for Deciding Drip Irrigation Products

Issue	Questions
Wall thickness	What kind of crop am I growing; is it permanent? Will I reuse the tubing? Is the tubing recyclable? How much do I wish to spend? What are the potential problems with physical or varmint damage to the tubing?
Emitter type	What kind of crop am I growing? Is the crop permanent? What are the potential problems with clogging? What about the field topography? How much do I wish to spend?
Emitter spacing	What is the spacing of plants down the row? What is the soil texture; sandy soil will mean closer emitter spacing?
Emitter flow rate	Size of zones
Service	What is the company’s reputation and proximity? Is there a knowledgeable representative close at hand?

crops, there will need to be consideration for weed control and damage to the drip tubing will likely lead to more maintenance costs. Another consideration, especially with crops on sandy soils, is placement of the tubing relative to the row of crops. Some specialists recommend placement of the tube in the center of the bed with the crops planted off-center (Fig. 5.2). Placement of the tube in the center of the bed increases the chances of more fully wetting the soil across the bed and this may be critical where some preplant fertilizer has been incorporated in the soil in the bed. Drip tubing and tape is recommended to be placed in the bed or on the soil with the emitters facing upward so the particulates are less like to accumulate in the orifice, rather be flushed outward.

Injection and Safety Equipment

Drip irrigation system designs should include certain safety equipment, especially if fertilizers and pesticides are expected to be used in the system. Typically, backflow prevention systems will be required by law to prevent the backward flow to the well of injected chemicals if the system shuts down unexpectedly during a chemical injection (Fig. 5.4). The backflow or check valve will help prevent the flow of

water backward toward the water source. An electrical fertilizer injector should have an interlock connection so the injection pump will shut down when the water source pump shuts down. Costs of a drip irrigation system vary widely depending on the size of operation and the need for peripheral equipment such as a computer, filtration, and fertilizer injection equipment. A small system for 10 acres may cost approximately \$10,000 to get the well, filtration, and main lines installed. Each year there may be at least \$200–300 per acre needed to replace the drip tape and some connectors.

Chemicals such as fertilizers, certain pesticides, and clogging-prevention chemicals can be injected into the irrigation system. Selection of the type of injection pump will be important. Some systems will need a source of electricity to operate the pump. Small farms may get by with pressure differential systems such as a Venturi-type injector. More information on injecting is presented later.

Filtration

Some water sources will contain physical or biological contaminants that may clog the drip emitter. Well water may contain sand or mineral deposits and surface water may contain algae, organic matter, or other particulates. Filtration by at least a 150 mesh screen is typically recommended for most drip irrigation systems to minimize clogging of the emitters. Depending on the water source the farmer should consider a filtration system such as a screen, disc, or media filter ([Haman and Zazueta, 2014a, 2014b](#)). Sometimes the water may contain certain chemicals such as iron that can be treated and filtered. Filtration removes materials that are in the water source or form (precipitates) early in the transfer of water from the source to the main lines. However, certain biological clogging agents, such as bacterial slimes, can form in the submains and drip tubing or tapes. These need to be dealt with by water treatment, which is explained later. These potential clogging issues dictate that a complete water analysis should be done to determine what kinds of potential problems can be anticipated that may necessitate treatment and filtration.

Operating the Irrigation System

Crop irrigation efficiency depends on knowledge about the crop's water requirements, the soil's water-holding capacity, and the grower's

ability to manage the irrigation system. Conceptually it may be helpful to think about irrigation in the same context of an economic budget with inputs and outputs of water. Underirrigation or overirrigation can lead to economic losses and to potential environmental impacts due to leached nutrients (from overirrigation). The first aspect of irrigation management is the knowledge of the crop's water needs across the growing season. This amount of water with rainfall makes up most of the input side of the water budget. A little extra water is needed to account for lack of 100% water delivery efficiency of the system, due to leaks or evaporative losses. The next important aspect to irrigation management is knowledge about the crop's root zone and the soil's water-holding capacity. This helps determine how much water can be held in the root zone without exceeding the "reservoir" and causing leaching below the root zone. The final part of irrigation management pertains to the particular drip system and its water delivery rate which determines how long the system will be run to supply the needed amount of water. These important aspects of irrigation management are discussed in the following sections. We will start with the field soil.

Soil Water-Holding Capacity and Available Water

An important aspect of drip irrigation management is to know the soil texture in the field and the volume of the root zone. The goal is to maintain some amount of water in the soil in the root zone—we will refer to this as the water "reservoir." Soil texture is the relative proportions of sand, silt, and clay in the soil. Clayey soil can hold a lot of water and sandy soils hold little. The ability of the soil to hold water is referred to as its water-holding capacity. Specialists can help calculate the soil's water-holding capacity or the farmer can derive this information from documents or fact sheets through the Extension System. [Fig. 5.7](#) shows the concepts of soil water content. Soil's water-holding capacity can range from 0.25 to 0.75 in. of water per foot of soil for sandy soils to 2.0 in. for silt–clay–loams. Irrigation specialists who design and provide the equipment for drip systems may be good sources of information. Not all of the soil water is available to the crop as some is held too tightly in the soil. It is the available water that is important for irrigation management. The farmer needs to know the volume of soil in the root zone for any particular stage of crop development. Knowing the volume of soil and the water-holding capacity can help

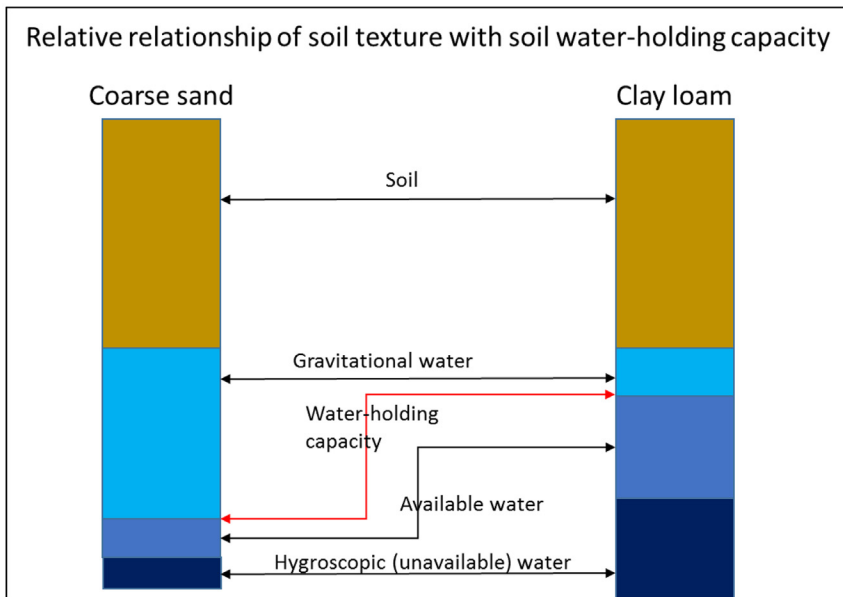


Figure 5.7 Generalized presentation of the types of water in two soil profiles. Water-holding capacity and available water contents of sandy soils are less than finer-textured soils. Courtesy from George Hochmuth.

determine the amount of crop-available water that the soil under a crop can hold. The farmer determines what portion of this available water will be allowed to deplete between irrigation events. Usually recommendations suggest allowing the crop to withdraw about 50% of the available water between each irrigation. Knowing the volume of water that can be held in the root zone and how much the farmer feels comfortable withdrawing between irrigation events can help determine irrigation frequency. It is analogous to determining how much money to withdraw from the bank account before replenishing the account. Sandy soil holds less available water than finer-textured soils. Therefore, irrigation frequency will be greater for crops growing in sandy soils. Rainfall must be included in the determination of irrigation frequency because rainfall will replenish the available water in the soil “reservoir.” This information will be part of the information in a checkbook or budget approach to manage irrigation. More information about this approach is explained below and there is considerable information available from various states’ Extension Services pertaining to the budget approach to manage irrigation.

Determining Crop Water Use

The second determination to be made by the farmer is how much water is being used by the crop. Cropping systems use water based on the amount of water taken up by the crops and the amount of water evaporated from the soil surface and crop. These processes combined are referred to as evapotranspiration (ET) and the volume of water is estimated mathematically involving various climatic factors for a well-maintain turfgrass as a standard plant system. These ET values are adjusted slightly, with a coefficient, depending on the crop being grown and the stage of growth of the crop. The resulting values are called the “crop ET” values. Crop ET values may range from 0.3 in./day for vegetables in the early growth stage to as much as 1.0 in. (or slightly more) per day for crops growing at maximum rate in midseason. Crop ET usually declines as the crop reaches the harvesting stage. Usually a farmer can obtain the crop ET values from published fact sheets from the Extension Service. Some states’ Extension Services have current and archived weather data from real-time weather stations scattered in the agricultural areas. Florida has the Florida Automated Weather Network (<http://fawn.ifas.ufl.edu/>) from where farmers can obtain real-time weather information and ET values from a station nearby. For example, the crop ET may be 0.15 in./day in May and rise to 0.25 in. in June in Central Florida, USA. These would be the amounts of water used by the cropping systems and would need to be replaced by irrigation, assuming no rainfall. The amount of water used by the crop is the output from the water budget when using the checkbook or budget approach to manage irrigation. Irrigation and rainfall are the inputs. Balance must be achieved through proper management of the irrigation system to minimize excessive irrigation and leaching and to minimize underirrigation which would lead to crop drought stress.

System Run Times

By knowing the amount of water used by the cropping system, the soil reservoir capacity, and the flow rate of the irrigation system, the farmer can determine the duration to run the irrigation system. This understanding can help determine operation times (“run-times”) to ensure the water (and any injected nutrients) will stay in the root zone. There is a caution that needs to be discussed here, particularly with drip irrigation systems. The ET volumes are typically expressed in inches of water and refer to an acre surface area (applicable to sprinkler

irrigation). However, drip irrigation does not wet the entire soil surface, but rather a narrow band of soil. Fig. 5.8 illustrates the soil-wetting pattern for drip irrigation. Water moves laterally and vertically from the emitter and the blue dye can tell the user how far the water moves before going below the root zone. The blue-dye test can help determine the volume of the root zone, that is, the reservoir. The goal is to keep the water (and injected nutrients) in the root zone. The blue-dye test can help the farmer determine and fine-tune system run times with particular drip tapes (Simonne et al., 2014). An example calculation is presented below to illustrate these concepts.

Since the wetted soil volume is less with drip than with sprinkler, run times will be shorter in individual duration, but more numerous during the day to meet the crop ET volume needed. For example, the farmer may run the drip irrigation system two to three times daily to apply the daily volume of water needed by the crop—fill the soil reservoir several times. Applying the total daily crop ET volume in one irrigation event with drip irrigation would run the risk of overfilling the soil reservoir and leading to leaching of nutrients. The soil reservoir may not be large enough to hold the entire day's worth of water. For this reason, it is important to know the soil's water-holding capacity, the root zone, and the daily needed irrigation amount.



Figure 5.8 Blue dye injected through the irrigation systems can show where the water has moved in the soil. Note the pattern under each drip irrigation emitter. The blue-dye patterns should touch laterally down the row, but not extend vertically below the bottom of the root zone. Photo courtesy from George Hochmuth.

The final consideration in determining the run time is the flow rate of the drip tape. Drip tubing may have a flow rate of 0.10 gal./min./100 ft up to 0.50 gal./min./100 ft. Typical drip tape used for vegetables will have emitters spaced 12 in. apart and have a flow rate of 0.5 gal./min./100 ft of row. For some vegetables the spacing may be slightly closer or farther than 12 in. Closer spacing may be needed in very coarse sandy soils and further spacing can be used in finer-textured soils such as loams. Irrigation system efficiency is usually about 90–95% for most drip irrigation systems so this will add a little extra time to the run to account for water losses due to leaks or evaporation.

An Example

Here is an example of how to pull together all the information above. This example is for drip-irrigated, plastic-mulched vegetables and is adapted from [Dukes et al. \(2015\)](#). This example assumes a sandy soil with an available water-holding capacity of 0.75 in./ft of soil, which is 20,370 gal. of water per acre in the upper foot of soil (1 acre-inch of water = 27,150 gal.). This is the amount of water that would be in the upper foot of soil over the acre. However, with drip irrigation we do not wet the entire acre; we wet only a fraction depending on how far the water moves in the soil. The amounts of water to wet the various volumes of soil (width $\times$ depth $\times$ length) in [Table 5.3](#) are therefore a fraction of the 20,370 gal./acre-foot.

The values in [Table 5.3](#) must be coupled with the crop water use. For example, if the ET (crop) is 5000 gal./acre/day (maximum growth stage) and the irrigation application efficiency is 90%, then the irrigation need is $5000/0.9 = 5560$ gal./acre/day. From [Table 5.3](#) we see that the soil will hold only 2100 gal. if the bed spacing is 5 ft and our wetted soil is 1 ft wide by 1 ft deep. Therefore, we need to split the irrigation amount so that we do not exceed the water-holding capacity in the root zone. For this example, we need $5560/2100 = 2.6$ events. We round up to three events each of $5560/3 = 1850$ gal./acre/event. Knowing the drip system application rate, we can calculate the duration to run the system. If our drip tubing applies water at 0.5 gal./100 ft/min. (43.5 gal./acre/min.), we need to run the system for $1850/43.5 = \text{about } 45$ min./event. We need three 45 min. events per day to satisfy the crop ET on that day. This calculation assumes we are using an allowable depletion of 50%, that is, we will allow 50% or 2100 gal. to be used.

Table 5.3 Maximum Water Amounts (in Gallons per Acre and in Gal./100 lbf) that Should Be Applied in a Single Irrigation Event for Vegetables Growing in Various Bed Spacings (Assuming Sandy Soil with an Available Water-holding Capacity of 0.75 in./ft and 50% Allowed Soil Water Depletion). Actual Daily Crop Water Needs May Exceed These Amounts so that Split Irrigations May Be Required During Peak Water Requirement

Bed-Wetting Width (ft)	Bed Spacing (ft)	Bed Length (100 lbf/acre) ^a	Gal./100 ft to Wet to Depth (ft)			Approx. Gal./Acre to Wet to Depth (ft)		
			1	1.5	2.0	1	1.5	2.0
1	4	109.0	24	36	48	2600	3800	5100
	5	87.1				2100	3100	4100
	6	72.6				1700	2600	3500
	8	55.5				1300	1900	2600
1.5	4	109	36	54	72	3800	5800	7600
	5	87				3100	4700	6200
	6	73				2600	3900	5200
	8	55				1900	3000	3900

^albf is linear bed feet. Some values have been rounded.

Water Application Uniformity

Water application uniformity is important and refers to all plants in the field receiving the same amount of water. Uniformity is especially important if the irrigation system is being used for fertilizer or chemical application. Farmers should test the irrigation system for water application uniformity. This test will prove that the system was designed and installed properly. Testing for uniformity also can be used during the season to check for any emitter clogging. Testing for uniformity is relatively easy to do and should include three parts: a test for system water application uniformity (collecting water from at least 18 emitters), a test for pressure variation (checking the system pressure at several locations), and a test for emitter performance uniformity (checking for other factors leading to lack of emitter uniformity). Detailed information on these tests and how to calculate the uniformity values is presented in [Smajstrla et al. \(2015\)](#).

Irrigation Controllers

Many small farmers may elect to control the irrigation by manually turning valves, based on a soil moisture indicating device such as a tensiometer. Automation can be achieved with various controllers ([Munoz-Carpena and Dukes, 2015](#)). With many crops and zones in the field, and with larger operations, some sort of automation is helpful because it frees up time for the farmer to work on other farm duties. Most importantly, automation helps remove “operator error” from the management of the irrigation system, such as forgetting to turn the system off at the appropriate time and running the risk of leaching fertilizer. Automation can be accomplished with simple time clocks or more sophisticated programmable controllers. Drip irrigation installers can recommend various types of controllers that will satisfy the particular farmer’s needs and economic situation. Some controllers can be placed in the home, office, or barn and can save data for future use. Some can troubleshoot problems with the system and shut the system down. Some can integrate weather data or soil moisture information and calculate irrigation needs as described above, turning the irrigation system on and off.

Soil Moisture Sensors

Most specialists recommend the incorporation of a backup method for managing the irrigation system that involves soil moisture monitoring.

Soil moisture can be measured directly by a gravimetric method or indirectly monitored by several moisture-sensing systems. There are several types of sensor systems that can be used to monitor soil moisture, including tensiometers, capacitance meters, neutron scattering, time-domain reflectance, or electrical resistance (Lamm et al., 2007; Munoz-Carpena, 2015). These methods vary in sophistication and expense, but all can help the farmer develop confidence in the particular management strategy being employed. Some soil moisture tools simply help the farmer “see” the soil moisture and the results of the irrigation management. Some sensors can interact with the controller to guide run times, making the system fully automated.

Clogging Prevention

Clogging can be a problem in some drip irrigation systems so that some technology needs to be in place to control the cause of the emitter plugging (Haman, 2014). The first step is to know the potential clogging problems—mineral, scale (precipitation), or biological, or a combination. Some problems like mineral particulates can be handled with filtration. Some problems require chemical treatment with filtration and flushing. There are various chemicals available in the market for injecting into drip irrigation systems to reduce clogging potential once the exact cause is known. Chemical clogging may be from iron oxide or limestone precipitation, and biological clogging can be due to certain bacterial slimes, sometimes in combination with iron. Bacterial clogging is fairly common especially where fertilizers are injected. The residual water in the drip tape heats up during the day as the drip tape lies on the soil surface or under the plastic mulch, making ideal conditions for bacterial growth. For many small farms, injecting hypochlorite (bleach) solution in the system will help reduce bacterial clogging. Irrigation specialists may recommend a habit of injecting a small amount of hypochlorite weekly to minimize clogging potential. Amounts of hypochlorite to inject must be carefully calculated so that excess does not damage the roots of the crop, especially of young crops. The typical recommendation is to inject enough hypochlorite to achieve a detectable level of “free chlorine” (using appropriate testing kits) at the end of a drip tape run. This approach lets the farmer know there was enough active ingredient to totally react in the water. Other clogging problems may need to be treated with acids or scale-inhibiting chemicals.

A backflow prevention system must be in place when injecting chemicals into an irrigation system (Boman et al., 2015). The backflow

system prevents injected chemicals from moving backwards into the water source if the irrigation system inadvertently shuts down for any purpose. A backflow system consists of several important components, a pressure relief valve, a check valve, and a low-pressure drain (Fig. 5.4).

Injecting Fertilizers Through the Drip Irrigation System

Vegetable crops typically need fertilizers to supplement the soil-derived nutrient supply. A fertilizer plan may include applying some of a particular nutrient throughout the growing season (Hochmuth and Hanlon, 2016). One of the biggest advantages of a drip irrigation system is its ability to apply fertilizers with the water. Often this process is referred to as fertigation (injecting fertilizers into an irrigation system). This capability gives the farmer a high degree of control over the fertilization of the crop. Certain nutrients can be applied in small amounts over the growing season, thereby reducing the chances of large-scale losses of nutrients at any one time. There are several types of injection systems that can be used for chemical injection into a drip irrigation system (Haman and Zazueta, 2014c) and the injection process can be automated. A simple Venturi-type injection system may be sufficient for a small farm (Fig. 5.9). A backflow prevention system will be required for the irrigation system that will also apply fertilizers. Fertilizers injected must be highly soluble forms of various nutrients so they do not clog the drip irrigation tubing or tape. Nutrients most often injected are nitrogen and potassium because these two nutrients are needed in the largest amounts by crops and therefore are most worthy

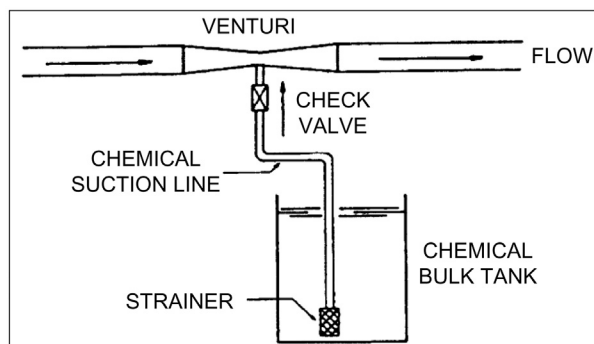


Figure 5.9 A venturi injection system for injecting fertilizers into a drip irrigation system. Available from: <http://edis.ifas.ufl.edu/wi004#IMAGE> WI:WI004F13.

of a high degree of management so that costs can be controlled. Also, there are easily available highly soluble forms of these two nutrients. For example, a mixture of potassium nitrate or potassium chloride and ammonium nitrate or urea might be used. Many fertilizer-blending companies supply liquid formulations of fertilizers ready for injecting. The liquid fertilizer can be supplied to the farm and held in a tank near the injection point of the irrigation system. Small farms may elect to purchase bags of the ingredients and make their own mixtures by dissolving the fertilizers in water. Farmers will need to be aware of the need to calibrate the injector pump and make careful calculations to ensure that correct amounts of fertilizer are being injected.

Injection of fertilizer is begun after the system has reached operating pressure and continued for the period of time that allows the needed amount of nutrients to be uniformly applied across the irrigation zone. Usually a short water run time is recommended after the injection period to flush the nutrients from the drip tapes. This flush time may be the second irrigation run time for the day if several irrigation cycles per day are needed. Research has shown that, for most soils, injecting fertilizer once per week is adequate (7 days' worth of fertilizer injected on 1 day). Nutrient needs of the crop increase during the season, reaching a maximum point, after which the injection rate can be reduced (Hochmuth, 1992). For example, nitrogen needs may be met by injecting 0.5–1.0 lb/acre/day of nitrogen in the first few weeks after transplanting tomato, increasing to 1.5–2.5 lb/acre/day as flowers form through fruit sizing. Some states' Extension Service recommendations provide details on fertigation for various vegetables in that state. Fertilization is not required in each irrigation, although some computerized systems can do this.

Flushing the System

Most specialists recommend routine flushing of the irrigation system to minimize the potential of emitter clogging. Flushing is especially important where anticlogging treatments are employed. Flushing removes the chemical precipitates or biological materials from the drip tubing. Flushing of the drip tubing or tape can be achieved by two means: manual or automatic. In manual flushing, the end of the drip tubing or tape is crimped or tied during normal operation. There are plastic fittings to place over folded tubing at the end of the row to prevent water from flowing or leaking. Plastic end caps can be fitted to the end of the tape. The ends of the tubing or tapes are then manually

opened for a short period of time to flush the system as the system is irrigating. Alternatively, automatic pressure regulating flush caps may be placed on the ends of the tubing or tape that open under low pressure and close when the pressure in the systems builds. These flush caps allow some flushing each time the system starts.

Reusing the Tubing or Tape

Growers are often interested in reusing the drip irrigation tubing or tape for a second crop, where two crops can fit into the same growing season. If reuse is possible, the grower may wish to consider polyethylene tubing with inline emitters or thicker-walled drip tape. Reusing the tube or tape is possible as long as the grower took care to minimize clogging during the first season. Reutilization is a good way to get more value from the drip tubing or tape purchase. Often in Florida, the first crop is desiccated with an herbicide or manually removed from the plastic-mulched beds. Then a second crop is planted on the same beds. In areas where second crops are not possible, the drip irrigation tubing and mulch are removed by hand or mechanically. There are various mulch and drip tape removal machines for use with polyethylene mulch systems. The machines lift the mulch and tubing from the soil and wrap it in a roll. The plastics can be discarded properly, often in a landfill. Sometimes the polyethylene mulch and tubing can be recycled where this option exists.

Summary

Drip irrigation is a relatively new irrigation technology (+/-60 years old) and is used on most agricultural crops in the world. The United States is a world leader in the use of drip irrigation and a source of much research-based information on the technology and management of the system. Knowledge of the quality of the water source and proper design of the system and components is important for efficient use of the system. While drip irrigation can efficiently apply water for crops, it can also be used to apply crop chemicals such as fertilizer. In some states, drip irrigation constitutes a nutrient and water best management practice by state agencies because it can preserve water quantity and reduce the potential for nutrient losses. Drip irrigation is a powerful part of the polyethylene mulch production system, especially for vegetables, that increases crop productivity and vegetable quality.

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6 High Tunnels

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Extending the growing and marketing season for specialty crops is important for sustainable food production. As global climate becomes more erratic and as growers face increasing risks from diseases, insects, and wildlife, protected culture tools which extend the traditional growing season and protect the growing crop from stress have become invaluable and profitable. High tunnels are the penultimate season extension tool available to specialty crop growers in the United States.

High tunnels are single or multispans, polyethylene structures which generally use no electricity or fossil fuel inputs to heat or ventilate the structure (Fig. 6.1). In temperate regions of the United States, high tunnels can facilitate year-round food production. The high tunnel is passively heated and ventilated. Most high tunnels are covered with a single layer or double layers of polyethylene plastic (4–6 mm; greenhouse-grade) and heat transmittance of $5.7 \text{ W m}^{-2} \text{ K}^{-1}$. A typical high tunnel has a useful life of 10–20 years if properly constructed and managed. The single or double polyethylene layer provides a stable microclimate for crop growth. By adding a second layer of polyethylene with an air pocket between the two layers of polyethylene, the average 24 h temperature is increased by approximately 4°C with only a 5–7% reduction in light intensity.

Over the past decade, high tunnel production has been rapidly expanding across the United States. The U.S. Department of Agriculture (USDA) Natural Resource Conservation Service initiated a cost-share program which has facilitated construction of approximately 5000 high tunnels across the United States in the past 5 years. The growth in construction and use of high tunnels parallels the growth of demand for local, fresh food. The development of institutional food programs such as the USDA Farm-to-School program has significantly increased the demand for year-round local food production. Local production and marketing reduces transportation and packaging costs which can be a significant production expense for produce growers.



Figure 6.1 High tunnel structures in temperate regions of the United States are used for year-round specialty crop production. Source: L. Jett.

High tunnels facilitate intensive crop production on a small land area and are amenable to sustainable farming practices such as intercropping, cover cropping, microirrigation, compost application, and biological pest management. Crops within the high tunnels are protected from environmental stresses such as drought, wind, hail, rain, and intense sunlight. The polyethylene plastic covering prevents soil erosion during high rainfall events. The dry environment within the high tunnel keeps the plant canopy dry and reduces some disease and weed problems. The high tunnel creates a microenvironment of elevated CO_2 , soil and air temperature which affects plant growth and development. The polyethylene covering affects the quality of light reaching the crop canopy which can also affect disease development.

High tunnels also physically exclude some pests from attacking the crop including insects and wildlife. As a result, many growers use high tunnels for organic production of specialty crops. High tunnels have been shown to increase marketable yield of many high-value specialty crops such as organic tomatoes.

High tunnels have significantly lower investment costs and annual operating costs than standard greenhouses. The cost of most high tunnels is approximately $\$2\text{--}5/\text{ft}^2$. With a single crop using one-third of the year, most high tunnels can be profitable within 3 years while multiple crops produced for 12 months can return a positive net revenue in 1–2 years.

Most high tunnels are constructed as permanent structures; therefore, the site chosen is the area for crop production for several years. However, there are movable high tunnel structures available through several greenhouse-manufacturing companies. Depending on location, building permits may be required. The site should have no history of

perennial weeds or diseases and should be well drained and free of large stones. A soil test should be conducted in advance of choosing the site for the high tunnel. A summer or winter cover crop can be planted on the site to improve soil quality. Since high tunnels are manually vented, they should be accessible. Water is an essential input for high tunnels, so access to water (surface, rainwater or well) is necessary. While most high tunnels do not require electrical inputs, some growers choose to have electric fans which circulate air or inflate air between double layers of polyethylene covering the high tunnel structure.

High tunnels do not have to be constructed on perfectly level land, but a building pad or terrace can be made prior to constructing the high tunnel. Slope along the length of the high tunnel will facilitate water movement but generally should not be greater than 3%. Slope across the width of the high tunnel (i.e., transverse slope) can be compensated by adjusting the height of the ground posts on either side to keep the high tunnel frame level. High tunnels can be constructed on land with as much as a 5% transverse slope. The construction pad can have sloping sides to channel water and snow runoff from the high tunnel structure.

The site should have full sun exposure and good air flow since these are essential inputs to passive ventilation of the high tunnel. Low areas that accumulate cold air (i.e., frost pockets) and water or sites close to a tree line or other structures which may cast a shadow on the high tunnel structure should be avoided. Also, areas with strong wind should have a windbreak to prevent excessive wind stress or snow accumulation against the structure.

Orientation or positioning of the high tunnel is site-dependent. The primary criterion should be maximizing passive ventilation or cross-ventilation of the structure. Therefore, for suitable ventilation, the high tunnel should be oriented so the length of the structure is perpendicular (i.e., at right angles) to prevailing winds at the site. Above the 40° latitude in the United States, most high tunnels are oriented in an East–West direction for maximum total light interception particularly during low-light months of winter.

High tunnels vary in length, width, and shape. Ideally, the high tunnel should be at least tall enough to walk in with ease (i.e., >7 ft [2.1 m]) or for equipment to be taken into the structure to till the soil, apply compost, or create raised beds (Fig. 6.2). Most high tunnels are 15–35 ft (4.5–9 m) wide; 9–15 ft (2.7–4.5 m) high, and up to 200 ft (60 m) in length. Optimal length for an individual structure with roll-up sides is approximately 100 ft (30 m). The primary criterion for high tunnel air volume should be ventilation. Lengths greater than 100 ft or



Figure 6.2 High tunnel structure and design is determined by the prevailing growing environment and cropping system.

widths greater than 30 ft may require a ridge vent to facilitate ventilation. Many growers will start with a short, wide structure (e.g., 30 × 48 ft) and add onto the length in subsequent years. A shorter, wider structure is superior to a longer, narrower structure since the former will have less area exposed to the outside environment.

Larger high tunnel structures tend to store more heat during the day and are less likely to overheat. At night, when maintaining a stable temperature is crucial, larger high tunnels are less likely to cool down as rapidly. In addition, a taller high tunnel allows warm, buoyant air to rise in the structure, facilitating convective ventilation.

The majority of high tunnels are stationary with growers rotating crops within or between seasons of each year. However, there is increasing interest in movable high tunnels which enable growers the opportunity to use a high tunnel over several crops throughout the year. Movable high tunnels also prevent the soil accumulation of fertilizer salts which can damage many high tunnel crops. Movable high tunnels can significantly increase the efficiency of high tunnel production. Most of the movable high tunnels are designed to move laterally down the field over blocks of separate crops and thus have the potential to provide protection or heat units to as many as four crops per season. Some movable high tunnels have been mounted on angle iron skids and essentially towed over the field. The latest permutation of movable high tunnels have wheels rolling on a bar-track. The wheels, in turn are attached to the bows. Ground anchors are used to secure the base plate of the structure against wind stress. The end walls simply are removed or flip outward allowing as few as two persons to move the structure over the crop. By moving the structure throughout the season, soil quality can be improved by growing cover crops over some of the blocks throughout the growing season. Movable high tunnels can be used

for production of annual and perennial crops. For example, a movable high tunnel can be used over a leafy green plot from December to March then moved to an early season tomato plot in March–May, then rolled onto a primocane raspberry plot for extended fall harvest through November. Growers who choose not to use a movable high tunnel will have several independent high tunnels devoted to specific crops and then rotate between high tunnels or between beds within the high tunnels.

There are two main structural designs for high tunnels: Quonset and Gothic types. Quonset structures have a round roof with slightly shorter and curved sidewalls while gothic structures have a pointed peak (A-frame) with straight sidewalls. Gothic structures tend to shed snow and ice better than Quonset structures. Gothic structures also allow for a peak or gable vent to be added to the structure which facilitates air movement and ventilation.

Sidewalls on the high tunnel structure are usually rolled up to facilitate cross-ventilation. Therefore, sidewalls should be at least 5 ft (1.5 m) in height to maximize ventilation. During inclement weather, the sidewalls are usually closed.

Temperature management is one of the most important issues related to high tunnel crop production. High tunnels can exhibit extreme fluctuations in temperature over a 24 h period. Most growers have constructed larger-sized high tunnels which enclose a larger air volume. Due to a larger enclosed air volume, larger high tunnels do not lose radiant heat as fast during the night and tend to not increase in temperature as rapidly during the day. Higher sidewalls facilitate better cross-ventilation. Ridge, roof, or gable vents are also very effective in moderating temperature within the high tunnel. Many plant physiological processes such as germination, flowering, pollination, fruit set, and ripening are linked to temperature and humidity. High tunnels should be monitored carefully for extreme temperature fluctuations. For example, in early spring, the period of venting is usually between 10:00 am and 04:00 pm. If not vented properly, a high tunnel can reach extremely high temperatures ([Figure 6.3](#)). For example, a 60°F day can result in temperatures reaching or exceeding 100°F within the high tunnel. The level of venting depends on prevailing winds, sunlight intensity, and crop(s) being grown within the high tunnel. The goal should be to keep daytime temperatures during the spring and summer within the optimal range for most warm and cool season vegetable crops. If the daily minimum temperature is lower than the physiological base temperature for the crop, the vents are closed and supplemental heating sources such as row covers are placed over the crops within the high tunnel.

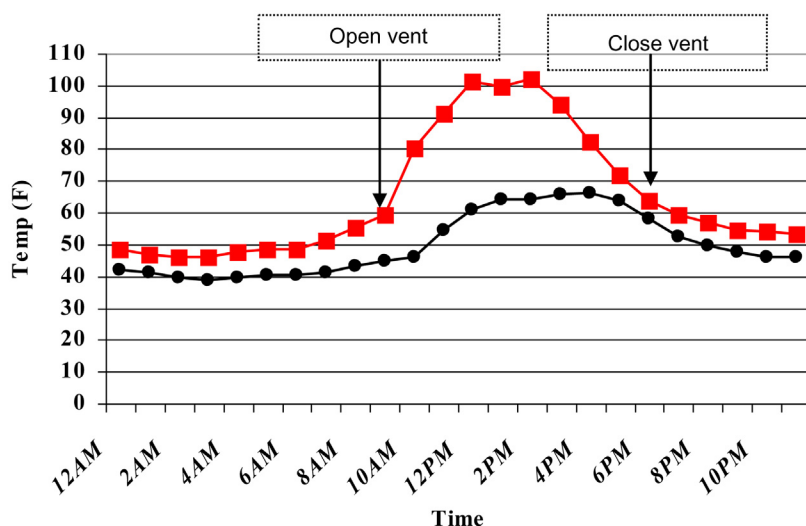


Figure 6.3 Temperature profile for a stationary, high tunnel in early Spring (38°N latitude). Source: L. Jett.

The majority of high tunnel producers in the United States use some form of supplemental heat. This includes row covers or the use of portable or stationary heaters that protect against a frost and heat air or soil within the high tunnel. Supplemental heat can dramatically increase the productivity of a high tunnel.

Water which runs off the high tunnel roof from rain can be impounded in polyethylene storage tanks and used to supplement irrigation of high tunnel crops. Rain gutters can be attached to the hip board or base boards and channeled to an aboveground or subterranean storage tank. A typical 30 × 96 ft high tunnel structure can use as much as 1500 gal. of water per week during maximal evapotranspiration. The use of rain gutters on high tunnels can provide approximately 50% of the irrigation requirements for high tunnel strawberries. High tunnel growers can impound water from the high tunnel to make the high tunnel more self-sufficient in external inputs.

Long-term soil quality and soil health within the high tunnel has become an issue for some growers who have stationary high tunnels. Growers should test high tunnel soil annually (preferably between each crop cycle) and monitor soil health and salinity. High tunnels provide an excellent environment for cover crops which can be grown between crop cycles as a rotation crop. Many high tunnel producers are evaluating soilless growing containers for production of high tunnel crops. This includes the use of static hydroponic or float-bed systems which

are very efficient in controlling root zone temperatures. Elevated, soil-less growing systems for crops such as strawberries, cucumbers, and leafy greens are becoming popular with high tunnel producers.

High tunnels can be used as three- or four-season structures. A four-season high tunnel structure is more durable with smaller gauge pipes or bows. Three-season high tunnels are large and are often called “field tunnels” covering multiple hectares per field. Field high tunnels are movable and the plastic covering is often removed in November each year and stored during the winter months. Field tunnels are particularly well suited for production of perennial vegetable and fruit crops such as asparagus, blueberries, brambles, tree fruits, and strawberries.

High tunnels can be used to successfully grow a diversity of crops throughout the year. At least three cropping systems can be established within a 12-month period in most temperate areas of the United States. The choice of which crops to grow within a high tunnel should hinge on those crops which have the greatest market potential within a region. While many crops can be grown in the high tunnel, some crops are best grown in the open-field using low tunnels or other season-extension tools.

Tomatoes, cucumbers, and leafy greens are the dominant vegetable crops produced within high tunnels, while brambles and strawberries are the dominant fruit crops in most regions of the United States. High tunnels fill a market window between early season greenhouse and field production of high-value crops such as tomatoes and peppers and thus can be used as a tool to have a continuous supply of products for market from the farm. Plants which have a vertical or compact growing habit are especially well suited for high tunnel culture since they utilize space more efficiently. Ideally a crop chosen for high tunnel production must have high yield per plant (unit area) and high value per unit of time and space. Intercropping, the growing of two or more crops in the same area over all or part of the growing season, is rarely practiced in the open-field but has been shown to increase production efficiency within a high tunnel.

In many regions of North America, growers use high tunnels exclusively for production of high-value, warm-season crops such as tomatoes (*Lycopersicon esculentum*), peppers, or cucurbits (e.g., cucumbers). High tunnels create a warm microclimate which accelerates vegetative and reproductive growth of fruiting vegetables. Two types of tomatoes are grown within a high tunnel: determinate and indeterminate cultivars. Determinate cultivars have one large fruiting cycle and are the best types of tomatoes to choose when early harvest is the prime objective.

Most determinate tomatoes are approximately 1.3 m in height and are trellised using inground stakes or wire cages. Indeterminate tomatoes are large-vine tomatoes (over 2 m in height and trellised) which have an extended fruiting cycle. Indeterminate tomatoes have large leaf areas which can significantly improve tomato fruit quality. Some indeterminate tomatoes are greenhouse cultivars, while others are heritage types. Indeterminate tomato cultivars are usually not as early to mature relative to determinate cultivars. However, their extended fruit production makes them the highest yielding tomatoes for high tunnels per unit time and space.

Other *Solanum* species such as peppers and eggplants thrive within the high tunnel environment. Many growers cultivate these types of vegetables under polyethylene low tunnels within the high tunnel to further accelerate heating. Many types of sweet and pungent peppers can be grown successfully within the high tunnel. The plants are usually planted in a twin row arrangement on 1.1 m-centered beds. The individual plants are spaced approximately 38 cm within row. To keep the plants upright, peppers and eggplants are staked.

Cucurbits are a productive crop choice for high tunnels. Specifically, production of melons (*Cucumis melo* and *Citrullis lanatus*), cucumbers (*Cucumis sativus*), and summer squash (*Cucurbita pepo*) are a suitable early or late season crop choice and can be rotated with other high tunnel vegetable crops. Cucumbers can be the most profitable warm-season vegetable crop choice for high tunnels (Table 6.1). The elevated temperature and dry microclimate within the high tunnel is conducive to high marketable yields of cucurbits.

Leafy greens can be a profitable fall, winter, and early spring crop within a high tunnel. In mid-latitude regions of the United States, lettuce should be seeded and established before day length and light intensity diminish in November. Spinach, kale, and Asian greens can tolerate low light and temperatures with very high marketable yields per square feet (Table 6.1). Root crop such as carrots, turnips, and beets can be seeded in early fall and harvested in early December or allowed to overwinter within the high tunnel for early spring harvest. Multiple planting of cool and cold tolerant crops (every 3–4 weeks) in the spring provides an even supply of high tunnel crops in late spring and early summer. Succession planting is not required in the fall and winter since crop growth is slower and the crops can be stockpiled within the high tunnel until harvest.

Strawberries are one of the most popular fruit crops produced in high tunnels. The typical field production season for this high-value crop

Table 6.1 Summary of Yield and Total Revenue of Annual High Tunnel Crops

Crop	ft ² /Plant	Yield/ft ² (lbs.)	Price/lb.	Total Revenue (\$) ^a	Time (days)	\$/ft ² /day	Rank
Beans (bush)	0.1	0.5	2.00	1800	65	28.00	10
Beets	0.2	1.25	2.50	5625	75	75.00	7
Broccoli	1.5	0.4	2.50	1800	80	21.00	15
Carrots	0.2	1.3	3.00	7020	75	94.00	6
Chinese Cabbage	1.5	2	1.65	2700	70	39.00	9
Cucumbers	4	2.5	3.00	13,500	65	208.00	1
Eggplants	6	0.7	2.00	2520	100	25.00	12
Kale	0.6	1.0	6.00	10,800	60	180.00	2
Lettuce	0.2	1.0	6.00	10,800	65	166.00	3
Melons	8	1.5	0.50	1350	120	14.00	16
Peas	0.1	0.5	2.00	1800	75	24.00	13
Spinach	0.2	1.0	4.00	7200	65	111.00	5
Squash (Summer)	8	0.6	1.00	1080	70	15.00	16
Raspberries	10	0.5	8.00	7200	365	27.60	11
Strawberries	2	0.8	3.00	4320	200	22.00	14
Peppers	4	2.0	1.00	3600	100	42.00	8
Tomatoes	8	2.5	2.50	11,250	100	113.00	4

^aSource: Lewis W. Jett, West Virginia University.

in the Mid-Atlantic region of the United States is mid-to-late May through June for matted row berries. High tunnels may give growers the opportunity to produce early season or late season strawberries. Strawberries are an excellent rotation crop for many other high tunnel crop choices. However, strawberries occupy a significant amount of time within the high tunnel and are not the most profitable crop choice per unit time.

High tunnels effectively expand the growing and marketing period for many crops. The protected environment created by the polyethylene covering provides protection from weather extremes and reduces disease and insect pressure. Combined with other plasticulture technology, high tunnels will continue to be a key ingredient to sustainable food crop production.

7 Plastics in Greenhouse Production

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Introduction

The use of plastics has revolutionized the greenhouse industry. Plastic is used for everything from the exterior greenhouse coverings, or claddings, to structural components, to nearly all aspects of the interior production systems, including pots, trays, irrigation systems and almost everything else. It is safe to say that without the use of plastics the greenhouse industry would be unrecognizable. Prior to the introduction of plastic covered greenhouses after WWII, greenhouses were covered with relatively small glass panes. These were heavy and required a lot of supporting sash bars which were generally wood, and that support required a lot of maintenance in the form of painting and reduced light transmission into the greenhouse. These glasshouses were expensive and time consuming to build. Plastic coverings, particularly polyethylene films changed all that. Suddenly you could construct an inexpensive frame to support large sheets of inexpensive plastic covering. This led to a rapid expansion of the use of greenhouses around the world to produce all sorts of crops (Wittwer, 1993). These greenhouses could have larger open spaces inside with fewer or in some cases no supporting columns facilitating better space utilization and greatly improved productivity. The use of polyethylene plastic sheeting or film as a greenhouse covering probably had more impact on the greenhouse industry as a whole than any other single application of plastics (Jacobson, 2011). But this was not the only revolutionary change in greenhouse production that can be attributed to the use of plastic. Another game changing application was the use of plastics in pots. By the 1970s and 1980s plastic pots had almost completely replaced the clay pots that were used previously. Clay pots were heavy and fragile which greatly limited growers ability to ship and market flowering potted plants, potted nursery plants, and bedding plants. Plastic pots were relatively inexpensive, rugged, and perhaps most importantly light weight.

The use of plastic containers caused another huge change in greenhouse production in the 1980s. The development of plastic plug trays with small individual cells combined with mechanical seeders capable of placing one or more seeds with precision in each of those individual cells revolutionized propagation practices in the greenhouse. Crop time was greatly reduced by eliminating transplant shock, and the whole process became much more efficient, with large-scale specialty propagators, or plug producers growing the plug seedlings while other growers focused on finishing the plants resulting in great economies of scale and labor requirements (Styer and Koranski, 1997). Another area where plastics completely changed a segment of the greenhouse industry is in their use in hydroponics. Modern hydroponic production systems depend on the use of plastics. Nutrient Film Technique (NFT), a common hydroponic production system for leafy greens and herbs, would not be possible without extruded plastic troughs and trays (Resh, 2013).

Plastic Greenhouse Coverings

The National Greenhouse Manufacturers Association (NGMA, 2004) classifies greenhouse covering materials by dividing them into three categories: Type I and Type II are both plastics, while Type III is glass. Type I coverings are thin films which generally range from 2 to 8 mills (0.002–0.008 in.) in thickness (NGMA, 2004). In most greenhouse applications these are used in a double layer with an air gap between them to improve their thermal properties (reduce heat loss) (Hannan, 1998). The most common material used in this way is polyethylene, where the two layers are separated by inflating the gap between them with air provided by a small fan. The two layers of polyethylene should be separated by no more than 4 in. Larger air spaces encourage convection and conduction heat losses. Additional layers could be added to increase thermal insulation but each layer reduces the amount of light penetration into the greenhouse. Other materials that fall into this category are ethylene vinyl acetate, polyvinyl chloride (PVC), polyvinyl fluoride, and polyester (NGMA, 2004). Type II greenhouse coverings are “Flexible” plastics, which are actually somewhat rigid. The most commonly used of these materials in northern climates are polycarbonate and acrylics. In the warmer southern climates fiberglass reinforced plastic (FRP) sheets are also common. Other materials in this category include PVC and polyethylene terephthalate glycol modified panels. These materials are often manufactured as multiwall sheets with a “ladder profile.” The most

common are twin-wall sheets but sheets with three or more layers are also used. As with plastic films additional layers result in energy saving but reduce light transmission and subsequently reduce crop yields. The air gap between the standard two-layer plastic greenhouse covering results in a 35%–45% reduction in energy loss regardless of the plastic used (Giacometti, 2011). Acrylic and polycarbonate sheets used for greenhouse glazing are sold as monolithic sheets, corrugated sheets, or multiwall or multiwall corrugated sheets. These “flexible” plastics may also be sometimes layered into composites with combinations of glazing plastics laminated to each other or laminated to glass.

The most common greenhouse shape in the world is a hoop house or Quonset style covered in polyethylene (Boodley, 1998) (Fig. 7.1). These houses are inexpensive to build and cover and can be flexible in size and configuration. A single hoop house is generally limited to about 30 ft in width, but hoop house roofs can be daisy chained together creating a gutter-connected greenhouse that can cover vast areas of ground (Fig. 7.2). Polyethylene films, or poly films, for greenhouse covering are manufactured by melting polyethylene resin pellets in a giant cylinder. The melted resin is extruded at high pressure through a large ring shaped die and a film bubble, or tube, comes out and is blown up into a cooling tower. At the top of the tower rollers at different angles compress the tube and fold it until it is flat and narrow. For sheet plastic the tube is slit and then rolled onto a cardboard core (Jacobson, 2011). The tubes can also be purchased on a cardboard core to provide a greenhouse grower



Figure 7.1 Polyethylene covered greenhouse with polycarbonate end walls. Probably the most common type of greenhouse in the world.



Figure 7.2 Cutter connected plastic covered greenhouse.

with the two layers of film needed to cover a “double poly” greenhouse all at once. Tubes are available in widths up to about 25–26 ft. Plastic is applied to the greenhouse structure by inserting a pipe into the cardboard tube creating metal axle. The plastic roll is hoisted up on one end of the greenhouse structure and the plastic is carefully unrolled over the top of the structure. The poly tube or sheet is then unfolded, pulled tight, and fastened into place with metal or plastic channel locks (poly-locks) that run the entire perimeter of the structure, or in the case of a gutter connected greenhouse the entire perimeter of that roof segment. Once the two poly sheets, or the poly tube is secured a small blower (Squirrel-cage fan) is installed to inflate the greenhouse. The air layer between the two layers of film acts as an insulator and also stretches out the plastic. This is important to reduce flapping of the plastic in the wind, which could damage the plastic covering or cause it to come loose from the fasteners. The poly-lock systems in use today are a vast improvement over the older method of securing the plastic by nailing it in place covered with thin wooden strips. Wooden strips would frequently come loose and chafing and pulling of the poly would often cause premature failure.

Greenhouse poly films are manufactured with a variety of additives included to increase the value of the film. All greenhouse plastics have UV inhibitors added to slow the degradation of the plastic when exposed to UV radiation (Jacobson, 2011). The films on the first plastic greenhouses would only last one season or sometimes less. With UV inhibitors modern greenhouse poly films last 2–4 years. Films are classified by the amount of inhibitors added and the expected life on a greenhouse. Poly films are rated to last 2, 3, or 4 years. Other materials can also be

added to poly films to alter their properties and improve their performance as a greenhouse covering. Anti-condensate films have a surfactant added that reduces condensation by spreading out the condensate and preventing large droplets from forming. This is an advantage in that condensate “raining” down on a crop can saturate the media in pots below the drips, increase the incidence of disease, annoy workers or customers, and can reduce light penetration. The surfactant in anti-condensate films is slowly carried away by the condensate. The more the condensation the faster the material is lost. In most cases the anti-condensate properties are lost within a couple of years. Since the surfactant is a surface treatment care must be taken to ensure that the treated side is facing down into the greenhouse in order to be effective as printed on anti-condensate films. Another fairly common enhancement to poly films are additives to capture IR radiation. These films conserve energy by trapping IR radiation from objects inside the greenhouse reducing the heat required to maintain greenhouse temperature and thus saving energy. These are useful in northern climates where savings from a “thermal” film might reach 5%–25% (Espi et al., 2006; Jacobson, 2011). Films can also be purchased that have light diffusing properties. Diffuse light can increase crop quality and yields. Colored films are also available. The most common is white which is commonly used in overwintering structures in nursery production (Fig. 7.3). The white plastic reflects much of the sunlight resulting in cooler inside temperatures. Other colors have been tried but in most cases have not had sufficient benefit to justify the added cost (Hannan, 1998).



Figure 7.3 White poly greenhouse covering.

FRP sheets used to be a common choice for commercial greenhouses (Nelson, 1991; Churchill, 2011) but now are most common in home, hobby, and DIY greenhouses. Fiberglass panels are either flat or corrugated, with the corrugated panels providing added strength. Flat sheets are sometimes used on sidewalls but corrugated sheets are almost always used for the roof. Fiberglass yellows and becomes brittle as it ages so a Tedlar film is often laminated to greenhouse fiberglass panels to improve weather resistance. Fiberglass is quite flammable so fire-retardant chemicals are also usually added. Light transmission of fiberglass sheets ranges from 87%–55% and decreases with age. Fiberglass greenhouse covering will last 8–10 years on a greenhouse before needing to be replaced.

Acrylic greenhouse coverings offer long-term clarity and a long useful life of 30 years or more (Churchill, 2011). Acrylic panels for greenhouse use are double skinned with an air gap between the layers providing insulation (Fig. 7.4). These sheets thus provide very good thermal properties compared to single layer plastics, fiberglass, or glass. Twin-wall acrylic panels are 8 or 16 mm thick and they can be recycled. The 8 mm sheets can be bent over a curved greenhouse roof. The 16 mm sheets are too rigid to bend and are used for sidewalls and end-walls. A common greenhouse configuration is to have acrylic or polycarbonate sidewalls or end walls and a double-polyethylene roof. The acrylic or polycarbonate sidewalls provide rigid, strong, long-lasting walls into which doors, vents, and fans can be installed, while the double-polyethylene roof greatly reduces the overall cost. Acrylic



Figure 7.4 Acrylic twin-wall greenhouse covering.

greenhouse panels are more costly than either fiberglass or polycarbonate. Acrylic is flammable whereas, both fire-retardant fiberglass and polycarbonate are much less flammable so care must be taken to ensure that heater vents will not cause it to ignite. Acrylic panels are more expensive than polycarbonate panels and require special mounting attachments to allow for their thermal expansion and contraction (Hannan, 1998).

Polycarbonate greenhouse panels are very strong, have excellent light transmission properties, and in a multiwall configuration provide excellent thermal insulation properties (Churchill, 2011). Polycarbonate twin-wall panels are available in a number of thicknesses from 4 to 16 mm (Nelson, 1991). Thinner configurations are flexible and can be bent to cover most arched greenhouse roofs. Triple-wall polycarbonate panels are 8 and 16 mm thick. Greenhouse polycarbonate panels are “coated” to protect the polycarbonate so it will not become yellow or brittle with age. The coated side must be installed facing outward (Fig. 7.5). Multiwall polycarbonate panels can be purchased with protective coatings on both sides for use in “open-roof” greenhouses. Polycarbonate panels are either smooth or have a light diffusing surface. Light diffusing polycarbonate has good light transmission properties, while diffusing as much as 100% of the light. In some cases crop yields have been shown to be higher under light diffusing polycarbonate than clear panels. Polycarbonate panels can also be purchased as single layer sheets or corrugated single layer sheets. These are more common in climates with



Figure 7.5 Polycarbonate greenhouse covering. Note the yellowed panel that was installed inside out.



Figure 7.6 Polyester composite fabric thermal curtain.

lower heating demand. Polycarbonate sheets are generally warranted by their manufacturers for 10 years and should last 20–25 years.

In most northern greenhouses, an additional retractable layer of plastic fabric is frequently added to the inside of the greenhouse. These curtains are added mainly as an insulation layer to reduce energy loss. They can be closed at night to provide an additional layer and opened in the day to allow maximum light transmission. These heat retention curtains can reduce energy consumption by 30%–50% (Parbst, 2011). Heat retention curtains are usually made from composite polyester fabrics (Fig. 7.6). Depending on the material used for the curtain and its light transmission properties, these curtains can also be used to reduce light during the day or as blackout curtains for photoperiod control in photoperiodic crops. The most common polyester fabrics for combined heat retention and greenhouse shading are made of alternating strips of clear and aluminized polyester woven together. Polyester heat retention curtains will generally last about 10 years.

Plastic Pots, Trays, and Flats

The development of plastic pots, flats, and trays transformed the greenhouse industry in the 1960s–80s. Today almost all greenhouse crops are grown in some sort of plastic pot. Their light weight and durability allowed potted plants and bedding plants to become a commodity that could be grown in a large wholesale greenhouse in one location and shipped to markets far from the production greenhouse. These materials also allowed plants to be shipped to and marketed from large mass



Figure 7.7 Pots used for branding.

marketers and big box stores. Plastic pots can be manufactured in a number of ways, but most are injection molded or thermoformed. In response to consumer demands for green products, several trends have emerged, including efforts to recycle pots, use recycled material in pots, and to use biodegradable materials (Petrovic, 2015). Plastic pots are available in a variety of colors, although the most common are white, green, and black. White plastic pots are not as suitable for some crops because the light that is transmitted through the pot restricts root growth. Plastic pots have become brand identifiers for plants, with special colors and imprints to differentiate branded plant products (Petrovic, 2015) (Fig. 7.7). Standardized plastic pots, trays, and flats transformed the greenhouse industry by allowing the development of mechanized and automated pot filling, planting and transplanting equipment. Prior to the development of plastic plug trays, seeds were planted by sprinkling them onto a seed flat or tray. Once germinated the mass of seedlings were separated (pricked out) and individually transplanted by hand into a single pot filled with media by hand, sometimes at the time of transplanting, or sometimes in advance. This was a time-consuming, labor-intensive process which often resulted in significant transplant shock and plant losses. Plastic plug trays and the codevelopment of automated precision seeders began the transformation of the greenhouse industry from small local growers and sellers to plant factories. High-quality precision seeding machines were expensive and to justify the cost some growers began to specialize in mass-producing seedling plugs. The manufacture and use of standard pots and flats also allowed the development of pot and flat fillers which further reduced labor and improved efficiency. Plastic pots and flats are well suited for use in automated media filling equipment



Figure 7.8 Greenhouse plug transplanter. Part of the automated plant factory made possible by plastic pots, flats, and trays.

because unlike the clay pots and wooden flats they replaced, they can be easily stacked and separated. The final step in this process has been the development of automated transplanters (Fig. 7.8). Not only did plastics redefine the greenhouse industry in this way, but also changed the flowering plant seed industry as well. Precision seeders and transplanters require very high-quality seed with consistent, predictable germination rates of close to 100%.

Plastics in Hydroponics

Hydroponics, the production of plants in water, usually inside a greenhouse has a number of potential advantages over field production of the same plants. Production is higher, quality is better, production can be year-round, water use is reduced, and the produce, particularly leafy greens and herbs is cleaner (Resh, 2013). Hydroponics is nothing new, but commercially it was not practical without the use of plastic. Although in theory any water-tight container could be used for hydroponics, in general, concrete or metal troughs do not work as well as plastic or plastic lined troughs. There are several reasons for this material difference, primarily it is because you are providing the plant all its nutrients in the water solution and because plastic is inert and does not react with the nutrient solution, it is the best choice. One of the most common commercial systems for hydroponic crop production is NFT (Nutrient Film Technique) in which a thin film of nutrient solution



Figure 7.9 Greenhouse NFT system planted with lettuce and herbs.

constantly bathes the roots as it flows through a channel that supports the plants (Fig. 7.9). The nutrient solution returns to a reservoir (usually plastic) and a pump in the reservoir recycles it back into the troughs. These systems are commonly used to produce leafy greens and herbs in the greenhouse. There are numerous variations on this system including aeroponics, and float culture, but all rely heavily on the use of plastics to make them possible.

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8 Horticulture Plastics

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Plastics are used in almost every aspect of horticulture from crop production to marketing, mechanization, and shipping. Plastic is used for covering structures, soil mulches, air handling systems, energy curtain, shade cloths, harvesting containers, irrigation systems, labels, and growing containers. Since many of these topics are covered in other chapters, this concentrates on the use of plastics in greenhouse and nursery-containers, also known as pots and or trays.

History of Container-Grown Plants

One of the earliest known uses of growing plants in containers was the hanging gardens of Babylon, Nineveh, and even earlier in Egypt. The historic gardens of Italy and Spain used clay urns to grow both edible and ornamental plants. By the 15th century, affluent gardeners developed orangeries and conservatories in cold climates of England, Germany, and Russia using large clay, wood, or metal tubs. The citrus plants were carried outside in summer and back into glasshouses for the winters (Wikipedia, “[Hanging Gardens of Babylon](#),” 2015; [Historic Royal Places](#)).

In 1788, King George III of England sent Captain William Bligh on the *H.M.S. Bounty* to the Pacific Ocean loaded with wooden and clay tubs to bring Polynesian breadfruit back to be grown in the West Indies. The first voyage was stymied by mutiny, which was immortalized by the movie *Mutiny on the Bounty*, but Bligh completed a second trip to Tahiti and successfully delivered 678 breadfruit plants in tubs to Jamaica. Today, daughter plants can be still be found in the Bath Botanical Garden of Jamaica ([National Tropical Botanical Gardens](#), 2016; [Alexander](#), 2016).

All of these historical horticultural examples used heavy clay, wooden, metal, and sometimes even stone containers as these were the only materials available. These choices continued until the 1950s.

Greenhouse and nurseries were thriving as World War II veterans returned home and began to build new housing. Magazines and TV provided motivation and inspiration for decorating and everyone wanted to landscape their home like the pictures in *Better Homes and Gardens*.

Yet the horticulture industry was still using wooden and clay-ceramic containers, the legacy of centuries of gardening. These pots were heavy, difficult to sanitize, rotted, or broke easily. Shipping was difficult and expensive. As a child born into a 1950s' greenhouse and nursery family, the author remembers nailing together wooden flats and carrying heavy 4 in. and 6 in. clay pots. Attempts to reduce both cost and weight resulted in experimentation with tarpaper pots, recycled paper pots, peat pots, and old food cans. Their disadvantages paved the way for plastic pots in the 1960s. Yes, plastic was the future in so many ways (Larson, 1993) (Fig. 8.1).

Many of the plastic pot pioneers were from Massachusetts including Lockwood Plastics, Union Plastics, Rodgers Plastic, and the retailer F.W. Woolworth Company. Germany was also a leader from late 1940s onward in development of plastic resins.



Figure 8.1 Therman Michael, Michael Bros. Nursery, Russellton PA, USA. Carrying clay pots c. 1955.

Plastic pots were lightweight, less fragile, and cheaper to ship and needed less storage than clay pots. What an advantage for a young budding horticulturist, such as your author, to be involved in such an innovative new product holding such promise. Yet older greenhouse growers hated them because of difficulty to grow in plastic compared to clay pots. Dr. Alex Laurie, renowned floriculture researcher and teacher at the Ohio State University helped pave the way when he said, “Plants in plastic pots will grow better than in clay” ([Broodley and Sheldrake, 1982](#)).

Specialized Growing Media

With the introduction of plastic pots, plants tended to developed root rots as older growing media stayed too wet. Plastic pots did not “breathe” or dry down the way clay pots did. In those days, growers used field soil as major component—a standard mix was two or three parts field soil, one part peat moss and one part sand. It was heavy, poorly aerated, and growers had to develop their own special soil mix. Good topsoil was difficult to find and could contain contaminants, herbicides, or pathogens.

What became necessary was special lightweight media that matched plastic pot growing systems that were disease- and insect-free and reliable from batch to batch. Horticulturists in both Europe and United States were working on developing new growing techniques. Professors Ray Sheldrake and James Boodley at Cornell University developed the soilless Peat-Lite in the 1960s. European researchers at places like John Innes Center developed media mixes, which they called composts.

With new growing media, specialized greenhouse fertilizers, soil, and tissue tests were developed by people such as Bob Peters of JR Peters, Inc., Allentown, PA, USA ([Broodley and Sheldrake, 1982](#); [John Innes Center, 2010](#)).

Today’s automated transplanting machines, robots, and computers all reduced labor cost and improved plant quality. Seedling, liners, plugs, and finished plants can be shipped long distances. Retailers are excited to sell new items such plastic hanging baskets, flower bowls, decorative pots, and garden baskets. Well designed, uniform, attractive, and versatile plastic containers allow the ingenuity of growers, plant breeders, design engineers, retailers, and marketers to flourish.

Without the versatile, reliable molded plastic pot, the horticulture industry would not have become the economic powerhouse it is today.

The Modern Plastic Growing Container

The greenhouse and nursery growers must be able to grow healthy plants economically, the retailer must have good shelf life, and most important and final, the consumer must have success in the garden and landscape.

Plastic containers provide the following benefits to horticulture industry:

- Standardization of weight and size;
- Adaptability to automation (Pokorny, 2013);
- Contain sufficient media to grow crop;
- Compatible with carrying trays, carts, and benches required for automation;
- Durable for use in greenhouse, perennial, and nursery crops;
- Provides for printing of point-of-purchase (POP) labels, scanning codes, grower address, and so forth;
- Shipping durability and attractiveness in retail garden centers;
- Used in hanging baskets, urns, and attractive merchandizing pots;
- Recyclability or reuse;
- Adaptability to new growing systems;
- Create successful gardeners.

James Schrader at Iowa State University estimates that about 800,000 tons of plastic are used in the United States each year, resulting in over 4.4 billion plastic containers. The preponderance of plastic pot manufacturers are using recycled plastic in their finished products. Nursery Supply Inc., Chambersburg, PA, USA, says that they can use up to 100% recycled plastic, excluding colors and additives. East Jordan Plastics, Inc., in South Haven, MI, USA, has achieved sustainability by using a closed loop of plastic manufacturing. Not only are they using the current plastic recycling technology but they are also using recycled plastic containers from garden centers and nurseries (Schrader, 2013b).

Injection-molded pots are strong, rigid, and economical and are easy to handle when filled. *Vacuum and thermoformed* containers are often used for very large containers that provide exceptional strength and long life. Aquatic landscape uses these containers for landscape ponds.



Figure 8.2 Example of commercially available plastic pots. Picture provided by Summit Plastics Company, Tallmadge OH, USA.

Since they are accurately formed, pots and trays work well in automation growing and shipping. The other advantage is that they can be coextruded with black on the inside and colors on outside. The attractive colors and printability make them useful as part of a POP and marketing campaign (see [Fig. 8.2](#)).

Container Standards

The confusion on container sizes culminated in 2003 when a Pennsylvania consumer complained to authorities that he had purchased a 10 in. hanging basket that was not 10 in. across. Since complaints had been lodged in several other states as well, guidelines were developed by a government and industry taskforce. Most states now require labeling of container plants for retail sale in metric or inches and must be placed on the container when sold.

To assist pot manufacturers and plant growers, the American Nursery and Landscape Association has published standards “American Nursery Stock Standards” and “Industry Guide to Marketing Container Plants,” available at their website (www.americanhort.org). The European Nursery Stock Association has a similar standard called “European Technical & Quality Standards for Nursery Stock” (www.enaplants.eu).

Landmark Plastics Corporation says on their website (www.landmarkplastic.com) that the most common manufacturing methods for pots are extrusion, thermoforming or mechanical forming, and injection molding. Examples of plastic products are as follows:

- Bedding packs and appropriate trays;
- Market packs, square or round pots, and carrying trays;
- Branded containers with logos, labels, and cultural information;
- Propagation plug trays, seeder trays, with space for 50–512 seeds or cuttings;
- Large containers for trees and shrubs from 1 to 300 gal.;
- Hanging baskets in many sizes;
- Decorative pots for retail in attractive colors and prints;
- Containers for water and fertilization conservation with built-in reservoirs.

Plugs trays are specialized plastic containers that allow for easy dislodging of seedlings and rooted cuttings and seedlings. If automated transplanting machines are used, containers must accommodate the method of seedling removal. Transplant machines have metal fingers that will remove and place seedlings into the larger pots, inspect them, and then pots will be moved into growing areas (Fig. 8.3).

Plastic hanging baskets come in a range of sizes from 6 to 18 in. Many basket designs are available; some even have planting holes in the sides of the container. Strong hangers are easily attached to the pots that support the combined weight of the plants and media when wet. Hanging baskets can be purchased with either external attachable saucers or internal saucerless reservoirs. A saucerless basket comes with a plastic disk that is placed on the bottom of the container before planting



Figure 8.3 Example of transplant machine that uses metal fingers to remove and place plugs into larger pots.



Figure 8.4 Example of greenhouse hanging baskets (left) and a decorative pot in the home garden as a focal point (right).

and that creates a water reservoir from which water can be reabsorbed into medium through capillary action.

We see more and more growers using pots with special colors and printed logos as part of branded marketing program. Plastic decorative containers, pot covers, and flower bowls are intended to compliment the flowering plant. In fact, monochromatic matching pots and flowers are the newest trend, as are hanging baskets with side embossed decorations that mimic stone or fabric. Today's consumers are opting for more and larger container gardens, moving away from planting in ground.

Gardeners will often spend a bit more money for the upscale look provided by beautiful containers. In fact, the container may be more important than the plants growing in them. This is especially true for parties or special events ([Fig. 8.4](#)).

Nursery Containers

Schnelle and Henderson at Oklahoma State University report that deeper nursery containers have more air-filled space (porosity) and produce better root growth for woody ornamentals than shallow pots used in the greenhouse industry. Unfortunately, deeper pots have narrow bases and tend to topple in wind, so growers choose to use pots that are slightly deeper than wide. Growing media usually consists of bark, sand, and peat moss ([Schnelle and Henderson](#)).

The nursery industry in the 1960s often reused tin food cans in 1, 2, and 5 gal. sizes—hence the term “gallon nursery container.” That

term is still commonly used, but today sizes are standardized. For example, #1 trade size has a top diameter of 7 in. and height of 8 in. and contains a volume of approximately 1 gallon, whereas #300 has a diameter of 58 in. and 250 gal. volume.

The round plastic pot is still the most common design used in nurseries. Blow-molded containers are commonly used in the nursery industry as they are strong, durable, attractive, and economical. As size of plants increase and volume of media becomes heavier, the pots are designed with ridged lips that can be used as a handle and for increased strength. Usually, nursery containers are then placed above ground on woven weed barrier cloth. However, as plants get taller, they tend to fall over in wind and rainstorms. To help prevent this from happening, a pot-in-pot growing system was developed. In addition to stability, it protects roots from heat and cold and allows plants to overwinter in place ([Pot-In-Pot Nursery Production, 2013](#)).

Pot-In-Pot

Pot-in-pot is primarily used for large trees and shrubs in pot sizes from #7 to #45. The permanent socket pot is placed into the ground and a removable pot is placed inside it with media and plant. Plants do not blow over, roots stay cooler, and harvest requires just lifting a lipped pot out of the socket. A size #7 pot can grow a 1 in. caliper tree, #15 pot grows up to 2 in. caliper, and #45 can grow 3 in. caliper tree (see [Fig. 8.5](#)).

Air-pruning Pots

Growing woody plants in containers have many advantages; however, one persistent problem is the development of “circling roots” or

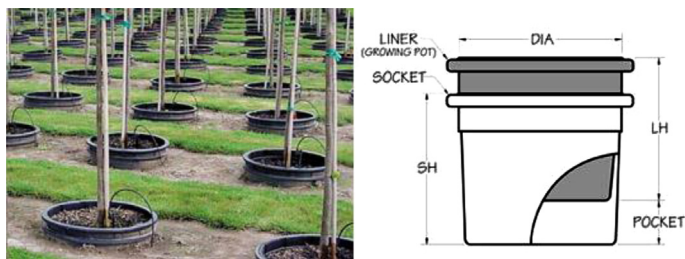


Figure 8.5 Example of pot-in-pot growing system and diagram of the two-pot Socket & Liner from Nursery Supply Inc., Chambersburg, PA, USA.

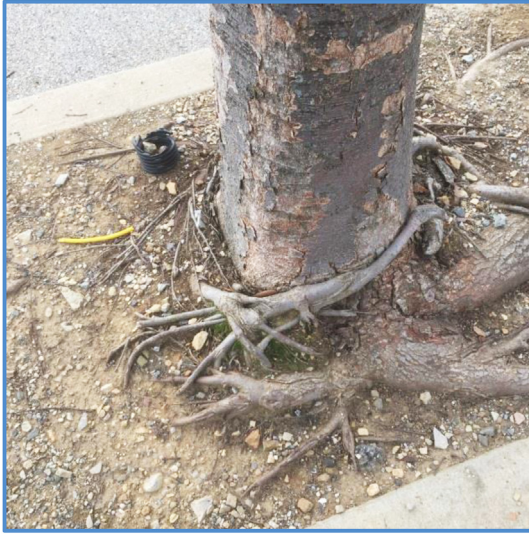


Figure 8.6 Example of girdling root in Japanese zelkova.

“girdling roots” also referred to as plants becoming “pot-bound.” Circling roots will eventually damage or kill plants once growing in the landscape. To prevent girdling roots from developing, horticulturists recommend slashing three-to-five vertical cuts in the root ball and then spreading the roots in final planting hole. This requires additional labor and often is not done, so plants suffer. Years later homeowners will see roots beginning to girdle the trunk at ground level (see [Fig. 8.6](#)).

Manufacturers and researchers have designed various methods to reduce or eliminate circling roots that develop in conventional nursery pots. One of the best methods is to coat inside of the standard pot with a root-regulating copper hydroxide compound such as Spin-Out. Research shows excellent reduction in circling roots with no reduction in plant growth or total root mass. Other methods include redesigning the growing container using open slots, grooves, or ledges to promote root branching. Some common brands of air-pruning pots include Smart Pot, Fabric Pot, Root Builder, Accelerator, Air Pot, and Root Trainer ([Crawford, 1997](#); [Nursery Supplies Inc., 2015](#)).

Reusable and Recycling

In Europe, reusable rather than one-time-use plastic trays are typical. Plastic tray manufacturers, such as SPID in Brittany, France, say their propagation trays will last 15–20 years. Polypropylene trays can be washed and sanitized for reuse in vegetables, flowers, strawberries, and herbaceous or woody perennials. Euro format trays 60 × 40 cm are used mainly for vegetable production, whereas the Danish format 54 × 30 cm is used for perennials and bedding plants. Propagation trays can contain from 40 to 600 cells, all designed for use in mechanized transplanting (<http://www.spid-trays.com/en/>).

In the United States, reusable trays are seldom used except for vegetable and ornamental crops where propagators and growers are in close proximity. Otherwise, transportation costs are prohibitive. Even though plastic pots can be recycled, most are not, and end up as trash. There is a great interest in recycling or repurposing as the preferred method of disposing of plastic pots and trays. The problem is recycled products are marketed globally and there is little demand for recycled flowerpots. Some consumers are even willing to pay a premium for nonplastic or recyclable containers. Meeting this consumer interest gives growers and retailers an opportunity to offer more eco-friendly products.

Charlotte Glen from North Carolina State Extension says that recycling plastic pots, packs, and flats is not always as simple as recycling soda and water bottles. Plastic drink bottles, polyethylene terephthalate plastic recycling code 1, are one of the most easily recycled plastics. Nursery and greenhouse pots are made from other types of plastic, including high-density polyethylene (code 2), polypropylene (code 5), and polystyrene (code 6). While every municipal recycling generally accepts code 1 plastic, fewer accept the types of plastic from which plant pots are made (Glen, 2013).

As plastic recyclers want clean plastic, but horticulture containers have dirt and plant debris attached, so a new approach had to be developed. Penn State University researchers James Garth, Mike Orzolek, and others have developed a method to turn horticulture waste plastics into a valuable fuel (Penn State Extension). The machine takes waste plastic (pots, trays, mulch, plastic film, row covers, silage bags, etc.), with its associated dirt and plant debris, heats it in an extrusion chamber and then a knife cuts into nuggets called Plastofuel. The Plastofuel will burn at 2000°F with minimal emissions. It can be burned by itself or

mixed with coal. More information is available from M. Lawrence at State University of New York, Alfred, NY, USA, who continues the research (<http://www.alfredstate.edu/users/lawrenmj>).

Plastic manufacturers have made great strides from using virgin plastic to using a majority of recycled plastic to manufacture containers. This is a major step toward sustainability, as it recovers plastic from the waste stream. But at the end of their useful life, the common plastic pots, often, still end up in landfills.

On the local level, many greenhouses, nurseries, and garden centers are working to collect pots, flats and packs for recycling. On the national scene, Lowe's Company has launched a program to collect used growing containers. In both cases, pots are sorted and reused in the greenhouse industry when possible and if found to be unusable, they are shredded and recycled into landscape timbers and other outdoor items.

Eco-friendly Growing Containers

Eco-friendly is listed as “recyclable,” “biodegradable,” or “compostable.” Recyclable means that materials such as aluminum, glass, or plastic can be collected and reprocessed to produce new items. Biodegradable simply means that the material will break down into carbon dioxide, water, and biomass in time; however, it could take a very long time! Compostable means materials that are not only biodegradable, more importantly, but it could also disintegrate within months under normal temperatures.

One of the oldest compostable containers is made from naturally occurring sustainable peat moss manufactured by the Jiffy Group since 1953. Other compostable pots are made from plant fibers, manures, processed chicken feathers, grains, and hulls. Some plastic pot manufacturers are substituting 40% chicken feather bioresins in conventional plastic pot manufacturing; however, even though biodegradable, chicken feather products are very slow to break down. CowPots are made of odorless composted cow manure in Rosemont, IL, USA, and will last months in greenhouse but will disintegrate in about 4 weeks when planted in soil.

Fiber-molded pots can be made from recycled newspapers, wood fibers, or coir and will degrade in about one year. The biggest problem with all natural materials is their fragility when wet and their difficulty for use in automated planting and shipping processes (Taylor et al., 2010).

Summit Plastic Company, Tallmadge, OH, USA, makes a line of compostable containers 100% free from petro-based polymers using rice hulls that breath and promote healthy roots. The pot will degrade when placed into garden soil. The great advantage is that rice pots can be made on the same machinery as standard plastic pots and will they work in automated greenhouse and nursery machinery.

Bioplastic

With the development of bioplastics, the industry is closer to achieving sustainability via reducing the carbon footprint and reliance on fossil fuels. Polylactic Acid (PLA) is a common bioplastic derived from biomass such as vegetable fats and oils, cornstarch, tapioca, microbiota, and other sustainable resources. PLA is a transparent plastic that can be processed by extrusion and injection into molded pots, agriculture films, sheets, and three-dimensional printing and spinning. PLA plastics will degrade in soils or sunlight. One of the problems with PLA is that it is only stable up to 110°F, whereas other compostable resins will tolerate higher temperatures and can be used for food containers (Bioplastics, 2016; <http://worldcentric.org/biocompostables/bioplastics>).

Iowa State University has developed a 100% renewable bioplastic that could be used for making growing containers. The biopolymers are derived from renewable distillers grain or soybean flour. James Schrader, Iowa State University Department of Horticulture, has tested the bioplastic pots and has found them to function as well as conventional fossil fuels plastics. Additionally, when bioplastic pots are planted into the soil, they will degrade and provide nitrogen fertilizer, or as James Schrader says this is, “Green Technology for the Green Industry” (Schrader, 2013a).

Not all bioplastics degrade quickly. Poly-3-hydroxybutrat, a biopolymer polyester, originates from bacterial processing of glucose or cornstarch and polyhydroxyalkanoates (PHA) are bioplastics that are derived from fermented sugars. These are long-lasting bioplastics found in automobile fuel lines, sport shoes, and electronic components and are considered eco-friendly and sustainable; no fossil fuel is used and they produce fewer greenhouse gasses and few hazardous wastes. These

specialized long-lasting bioplastics are not used in pot manufacturing (Bioplastics, 2016).

Certification groups in Europe (DIN, CERTO) and United States (ASTM) verify plastics as biodegradable, compostable, and produce no eco-toxicity. Certified compostables are categorized as either Home or Industrial. Home compostable pots are made of coir, peats, rice hulls, paper, manures, and bioplastics that break down in soil or home compost pile at normal temperatures in months, whereas, Industrial compostables requires high temperatures in specialized industrial factories (<http://worldcentric.org/biocompostables/bioplastics>).

Summary

Very few inventions have had such the dramatic influence on growing, shipping, and marketing of horticulture crops as plastic. Besides growing containers, plastics are used in:

- plastic films for roof and shade greenhouse covering,
- plastic mulches for soil covering in vegetables and fruits and ornamentals,
- food grade plastic bins for harvest, storage, shipping, and transport,
- chemical and fertilizer containers,
- bird netting on blueberries, cherries, strawberries, grapes, and so on,
- irrigation pipes, emitters, drip tapes, sprinklers, tanks, fittings, and valves,
- consumer packaging,
- point-of-purchase information, signage, labels, and ties,
- sprayer tanks, nozzles, and pump parts,
- rope and string twine, and
- molded products of all kinds including plastic pots.

Use of alternative containers and bioplastics can reduce the chemical footprint and waste generated by horticulture, but especially nurseries and greenhouses. Now that alternatives compostable and recyclable containers are available, they must become competitive with conventional plastic to make them a routine choice for commercial growers.

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9 Plastics in Animal Production

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Polymers and Types of Plastic Used on Livestock Farms

The demand for plastics in agricultural applications has increased to a great extent throughout the world over the past decade (around 15% of the world's total consumption of plastic) and has reached 3.6 million tons of plastic usage for agricultural films in 2013 (Vittova, 2013). Most of the plastic utilized in agriculture is used for the production of polyethylene (PE) films, which are used for greenhouses and tunnels, as mulching to cover soil, as bunker silage covers, and as bale-wrap films. About 59% of the manufactured plastic was used in Asia for agriculture purposes in 2013, while 15% was used in Europe, 8% in North American Free Trade Agreement, and 6% in Latin America. In Europe, approximately 45% of the plastic utilized in agriculture is destined for silage packaging. This percentage ranges from 20% in Italy to 80% in Nordic countries (Vittova, 2013).

Polymers and Their Products

The main polymers used for producing plastic products that are utilized on livestock farms are low-density polyethylene (LDPE) and polypropylene (PP). LDPE is utilized to produce almost 70–85% of agricultural plastic products, while PP is also utilized for some other applications, such as for strings and nets to tie round bales. The main plastic products utilized on livestock farms and the polymers used to produce them are reported in Table 9.1. Most of the plastic consumed on livestock farms is utilized as LDPE films for animal feed conservation purposes. This plastic then needs to be disposed outside the farms when it is no longer usable, thus representing a cost for the farm. Kuzin and Savoie (2001) estimated a plastic waste on Canadian farms of 0.3 kg/t of dry matter (DM) for bunker silos, 2.1 kg/t of DM for

Table 9.1 Polymers and Their Applications on Livestock Farms

Application	Typology	Polymers
Plastic film to cover horizontal silos and stretch film to wrap bales	Film	LDPE, linear LDPE, and coextruded PE-EVOH
Mulch films for cereal crops	Film	LDPE and LLDPE
Plastic bags for grain storage	Film	LDPE
Solid fertilizer containers	Film and Fabric	LDPE and PP
Seed packaging	Film and Fabric	LDPE and PP
Feed and vitamin supplement packaging	Film	LDPE
Liquid fertilizer and agrochemical containers	Bottle	LDPE and HDPE
Veterinary medicine containers	Bottle	HDPE
Hoses and nozzles for irrigation	Pipe	PVC and LDPE
Net to tie bales	Net	PP, LDPE, and HDPE
Strings and ropes	String	PP

HDPE, high-density polyethylene; PE-EVOH, polyethylene ethylene vinyl alcohol copolymer; PVC, polyvinyl chloride.

tubeline-wrapped bales, 2.5–2.7 kg/t of DM for individual round bales wrapped with 4 layers, and 2.0 kg/t of DM for bagged silos.

Amount of Plastic Used on Farms

The quantity of flexible plastic film used on dairy farms has been estimated considering the data from two surveys, one conducted in Italy (Borreani and Tabacco, 2014) and the other in Ireland (Hamilton et al., 2005); the former survey has been considered as representative of southern Europe and the latter as representative of northern Europe. Climatic conditions are known to influence the consumption of plastic used for forage conservation as they can lead to a shift from haymaking to silage conservation, especially in northern Europe where ensiling represents more than 80% of the conserved forage DM (Wilkinson and Toivonen, 2003).

The objectives of the Italian survey were to obtain information about the typology of plastic used on farms, the yearly amount of plastic purchased, and the costs and methods of its disposal. The typology of

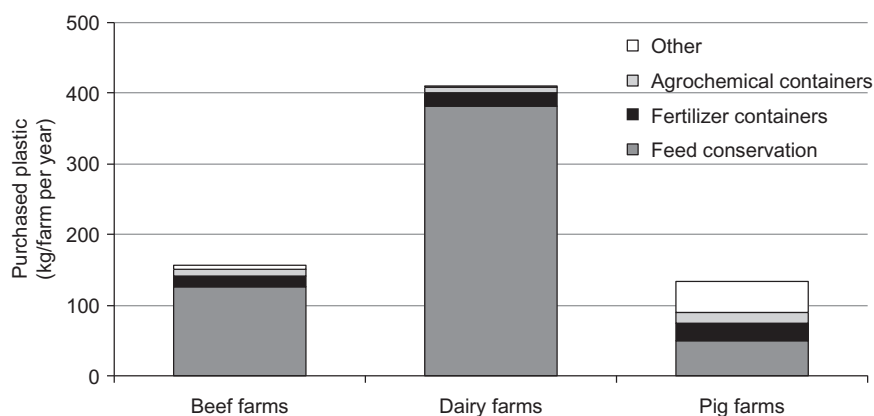


Figure 9.1 Plastic purchased yearly on livestock farms in northern Italy split according to the final use.

livestock farms was found to influence both the amount of plastic consumption and the type of plastic manufacturing (Fig. 9.1). The films utilized for silage conservation represented 80% and 93% of the plastic purchased yearly on dairy and meat farms, respectively, while it represented only 37% on pig farms. The 120 livestock farms involved in the survey were chosen to be representative of the intensive dairy and meat farms of the Po plain (Italy). Most of the farms produced corn silage (with a mean DM content ranging from 30% to 38%), which was stored in horizontal silos covered with LDPE of a thickness ranging from 100 to 250 μm . This means that a 50 by 12 m plastic film, weighing about 110 kg, is necessary to cover a 40 m long, 10 m wide, and 2.5 m high bunker silos (around 650 t of silage). Therefore, the plastic consumption for 1 t of silage is 0.17 kg, which means about 0.53 kg/t DM. If the silo walls are also lined with plastic film, the amount of plastic consumption increases to 0.28 kg/t of silage (corresponding to 0.87 kg/t DM). All the surveyed farms produced hay bales that were tied with LDPE nets. The mean net consumption is about 0.20 kg/bale. Over 80% of the farms produced wrapped bales in some periods of the year (spring and fall), utilizing individual wrapping with four to six layers of 25 μm LDPE stretch film. The mean film consumption ranged from 0.7 to 2.1 kg/bale, in relation to the bale diameter (1.2–1.8 m) and number of layers applied.

The other plastic material utilized on farms was for feed, fertilizer, and pesticide containers. The fertilizers were stored either in large bags (PP fabric) containing 500–600 kg or small bags (LDPE-sealed film)

with 40–50 kg of fertilizer. The mean plastic consumption ranged from 2 to 6 kg/t of fertilizer, depending on which type of bag was utilized. The agrochemical storage containers, mainly made of HDPE, only utilize a small amount of the plastic consumed on the farms.

In short, it has been observed that the plastic films that are utilized to cover silages, the stretch films that are used to wrap bales, and the net that is used to tie bales constitute most of the plastic consumed on farms. The plastic films that are utilized to cover bunker silages represent from 33% to 45% of the entire amount of plastic purchased by dairy farmers for feed conservation, depending on herd size (Fig. 9.2). Bale wrapping is adopted widely on dairy and meat farms because of its greater flexibility, and the plastic consumption of stretch film represents about one-third of the plastic consumption of these farms. The net that is utilized to tie hay, haylage, silage, or straw bales can represent

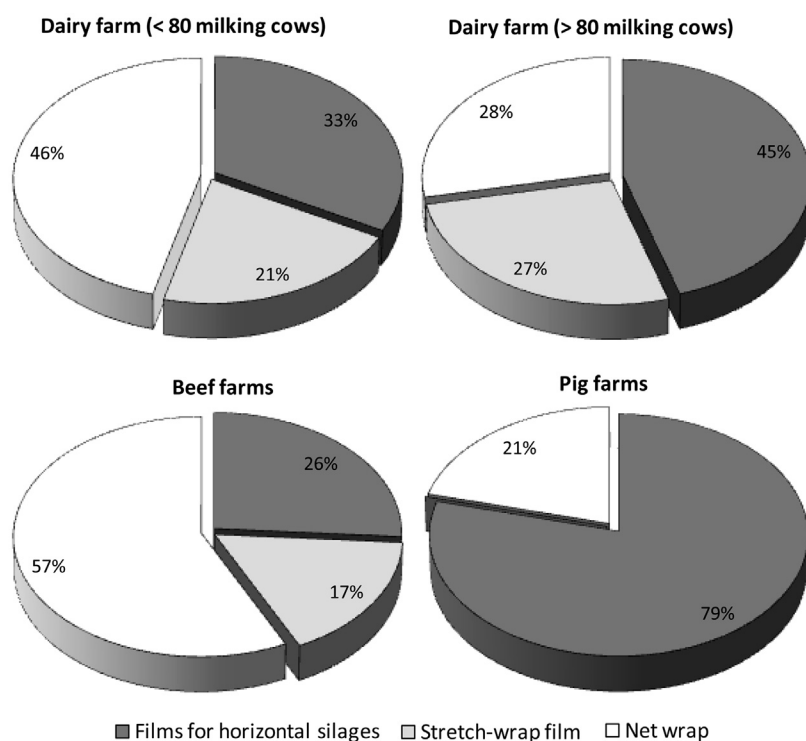


Figure 9.2 Distribution of plastic consumed on livestock farms for animal feed conservation in northern Italy. Adapted from F&F Biopack, 2014. Project: FEED & FOOD PACKAGING—Film biodegradabili per la sostenibilità ambientale della filiera agro-alimentare [Biodegradable films for the environmental sustainability of the agro-food chain]. POR. FESR 07-13-ASSE I.1.1, Years 2011–2013.

up to 40% of the plastic consumption of a farm. The total amount of plastic purchased yearly by livestock farms in northern Italy ranged from 0 to over 700 kg of film to cover silages, from 40 to over 800 kg of net to tie bales, and, on farms that used wrapping as their main forage conservation technique, this amount reached up to 500 kg of stretch film.

The plastic consumption per unit of land surface presents a mean value of 13 kg/ha with peaks that are close to 25 kg/ha per year. These values were lower than those on horticultural farms that use greenhouses or mulch, where the average plastic consumption ranges from 1200 to 1700 kg/ha per year to cover greenhouses and from 300 to 700 kg/ha per year for mulching (AlterEco, www.life-pianalto.org/documents/Progetto_Filiera_teli_agricoli.pdf). When plastic use is related to dairy cow number, an average 10.3 kg of plastic is utilized yearly, of which 3.9 kg/cow is utilized to cover bunker silages (F&F Biopack, 2014). Levitan et al. (2005) conducted a survey on plastic use in dairy farms in the Central Leatherstocking-Upper Catskill Region of New York State, USA, and reported that 3.4 kg of plastic film is used yearly per cow. The plastic consumption per ton of forage DM conserved by means of different methods is reported in Table 9.2.

Hamilton et al. (2005) conducted a survey on 961 Irish farms with the purpose of quantifying the primary and postprimary use of PE- and PP-based products used for packing fertilizer, mulching maize, tying silage bales, and sealing silage. The plastic used per unit of farm surface was 4.7 kg/ha of new film to cover pit silages, plus 3.6 kg/ha of

Table 9.2 Plastic Utilization (kg) per tonne of Stored DM on Livestock Farms

Plastic Use	Consumption of Plastic (kg/t of DM)		
	Mean	Minimum	Maximum
Plastic film for corn silage in bunkers	0.73	0.17	1.47
Plastic film for grass silage in bunkers	1.05	0.27	2.10
Stretch film to wrap bales	2.80	2.50	4.85
Stretch film to wrap inline bales	2.36	1.90	2.87
Plastic bags for individual bales	6.37	5.15	7.71
Plastic bags for grain storage	1.55	1.31	1.87
Net to tie bales	0.62	0.59	0.67
Twine to tie bales	0.50	0.46	0.57

film reutilized from the previous year; 21 kg/ha for baled silage stretch film; 2.5 kg/ha for baled silage twine/netting; and 1.1 kg/ha for fertilizer bags. Furthermore, in recent years, plastic mulch has been used on corn for silage in Ireland on around 4000 ha ([Hamilton et al., 2005](#)). The aim is to use photodegradable plastic that breaks down over the growing season and which can be used for two main types of mulching: the punch plastic system, developed in France; and the complete cover system, developed in Ireland ([Hegarty, 1998](#)). The punch plastic (12 μ m thick; 88 kg/ha) and complete cover (7 μ m thick; 51 kg/ha) systems are used on 16% and 84% of the area mulched in Ireland, respectively ([Hamilton et al., 2005](#)).

Plastic Film for Animal Feed Storage

Forage crops are the primary source of dietary fiber in rations fed to ruminant animals, and, in most parts of the world, forage conservation is a key element for productive and efficient ruminant livestock farms. Forage can be preserved as either hay or silage. Silage conservation depends on a combination of anaerobic environment and the acidification that occurs when a sufficient amount of lactic acid is produced by the population of lactic acid bacteria present on the forage at harvesting ([Pahlow et al., 2003](#)). The most important factors that can influence the preservation efficiency of forage during ensiling are the degree of anaerobiosis reached in the filled silo and its maintenance over the entire conservation period ([Woelford, 1990](#); [Borreani et al., 2007b](#)). Therefore, this technique requires an absolutely airtight environment which, until the 1950s, could only be attained through the use of constructions made of concrete or steel. The introduction of plastic films can be considered a revolution, as their use has allowed all farmers to benefit from the advantages of ensiling. Farmers can choose from a wide variety of silo types: horizontal silos with (bunkers and trenches) or without walls (piles and clamps), wrapped or bagged bales (round and square bales; wrapped individually or inline), and pressed bags ([Muck and Shinnery, 2001](#)). While silage can be successfully made in all of these types of silos, each type suffers from specific management issues and needs the use of one or more plastic films to create an anaerobic environment. Silage bags, bale wraps, and plastic bunker silo covers are the main plastic film products used on dairy farms. Nowadays, most of these films are made of LDPE and, since recently, of LDPE

coextruded with polyamides (PAs) or EVOH (Borreani et al., 2007b; Borreani and Tabacco, 2014).

History of the Development of Plastic for Silage Conservation

A milestone of great significance for ensiling, and which was introduced in the early 1950s, was the advent of the use of plastic sheeting to cover silage (Anonymous, 1953). This innovation led to a revival of corn silage being preserved in horizontal silos throughout Europe from the early 1960s. The years of the main milestones in silage technologies and silo covering, after the first use of plastic for silage conservation, are reported in Table 9.3. Plastic films have been used since the early 1950s to cover small tower or clamp silos (Anonymous, 1953; Schukking, 1976). The earliest sheets were made of polyvinyl chloride (PVC) and were used to protect small field clamp silos from rain ingress. In 1960, a researcher in silage said: “[...] *Although one may assume a priori that covering reduces waste, nevertheless quantitative measurements on top and side wastage do not appear to have been made, and the writer met with no active interest in this problem. Without such measurements the economics of silage covering cannot be calculated, yet the British Government subsidises the building of covered silos, while quite expensive plastic covers are now being marketed everywhere*” (Lancaster, 1960). The cost of 120 μm thick plastic films in PE at that time was relevant and it was therefore suggested: “[...] *The economic use of plastic covers demands that the geometry of the silo should be such that the finished silage presents the minimum surface area to be covered, whereas the self-feed silo tends to produce maximum surface area per unit volume of silage*” (Lancaster, 1960). From the beginning of the 1960s, sheets began to increasingly be made of PE and they included better plasticizers and ultraviolet (UV) stabilizers to prevent the material from disintegrating under sunlight (Wilkinson et al., 2003). Polyethylene was chosen because of its suitable mechanical characteristics and low costs and because of its ability to create anaerobic conditions of the ensiled mass.

The next major innovation appeared in 1965 when a graduate student at Iowa State University, Virgil Haverdink, sought out Wesley F. Buchele, a professor of Agriculture, to decide on a research topic for a master thesis. Haverdink suggested, “Let’s build a large, round baler!” Harvedink had his off-the-ground big baler prototype working in 1966 (Quick, 2007). The first material used for tying bales was

Table 9.3 Innovations in Silage Technologies and Coverings

Year	Innovation	Silage Typology	References
1950	Plastic film to cover silage	Horizontal silos	Schukking (1976)
1954	Plastic film in PVC (200 µm) and in PE (100–150 µm) to cover silage	Horizontal silos	Larrabee and Sprague (1957) ; Staff (1957)
1956	Plastic film in PE (120 µm)	Horizontal silos	Lancaster (1960)
1957	Trials with neoprene-nylon blankets to cover silage	Horizontal silos	Gordon et al., (1961)
1960	PE film to cover baled silage	Baled silages	Cropsey et al. (1966)
1966	First big round baler prototype	Baled bales	Quick (2007)
1972	PE bags (120 µm) for baled silage	Bagged silages	Ciotti (1992)
1982	Wrapped bales with stretch LDPE film (25 µm)	Wrapped bales	Anonymous (1996)
1984	First bale wrapping machine by Kverneland group	Wrapped bales	Anonymous (1996)
1989	PP or PE net to tie round bales	Wrapped bales	Anstey and Ardueser (1991)
1997	Coextruded plastic film PE-PA-PE (45 and 120 µm)	Horizontal silos	Degano (1999) ; Borreani et al. (2007b; 2014)
2000	First prototype of biodegradable stretch film	Wrapped bales	Keller (2000)
2003	Innovative three-dimensional round bale wrapping system by Vicon	Wrapped bales	Bisaglia et al. (2003)
2005	First prototype of coextruded OB stretch film PE-PA-PE (25 µm)	Wrapped bales	Borreani and Tabacco (2005)
2007	PE film to tie round bales	Wrapped bales	Bisaglia et al. (2011)
2008	First trial on experimental bio-based biodegradable film	Horizontal silos	Borreani et al. (2010)
2009	First prototype of coextruded high OB stretch film PE-EVOH-PE (25 µm)	Wrapped bales	Borreani et al. (2009)
2010	Prototype of bio-based biodegradable film to cover silage	Horizontal silos	Borreani et al. (2010) ; Spadaro et al. (2015)
2012	Special EVOH-coextruded films with lowered oxygen permeability	Horizontal silos	Borreani and Tabacco (2014)

twine and this became the most commonly used method for securing round bales till the 1990s. Net wrap was introduced on round balers in the late 1980s (Anstey and Ardueser, 1991; Taylor et al., 1994). The perceived advantages of net, compared to twine wrap, include greater baling productivity (only a few rotations of the bale are required to wrap the bale with net, compared to 20–30 rotations with twine), lower losses during wrapping, better bale integrity during handling and transport, lower outdoor storage losses, and better stretch film application if a bale is made for silage (Shinners et al., 2009). The baler purchase price is higher for the net wrap option, which costs roughly 15–25% more than a baler with the twine option only (Shinners et al., 2009). However, the savings in fuel, labor, and storage losses associated with net wraps may offset the additional costs (Shinners et al., 2009; Taylor, 1995).

Big bale forage packaging systems became popular in the 1980s because of their high labor efficiency. Owing to the poor weather conditions during forage harvesting in temperate areas throughout the world, it is difficult to obtain hay that is dry enough to keep in big bales without molding or without incurring large field losses from leaf loss or weather damage. One solution is to bale the forage moist and then encase it in plastic so that it ensiles (Nicholson et al., 1991). In the early 1970s, field-wilted round bales were made in 120 μ m thick PE bags to improve forage conservation efficiency. From one to three round bales were stored in each plastic bag, which was tied with rope to seal it. Defective sealing, especially at the neck of the bag, allowed air to penetrate the bale and, as a result, bagged silages often showed mold development and extensive aerobic deterioration (Wilkinson et al., 2003).

In 1982, two Australian businessmen (Peter Johnstone and Kerry Good) formed Integrated Packaging Group (IPG), a privately run, Australian-owned company which specialized in the distribution of LDPE stretch-wrap film for the industrial market (Anonymous, 1996). IPG has since grown to become the largest local manufacturing specialist of plastic stretch film and associated equipment in Australia. At that time, an Australian cattle farmer (Ken Williamson) met Johnstone and told him about his disappointment in the use of silage bags to conserve round bale silage. The idea of replacing bags made of LDPE with wrapping the bales in LDPE stretch film thus arose, in a similar way to wrapping loaded pallets in the industrial field (Anonymous, 1996). In 1982, the first wrapping round bale farm trial using transparent PE

stretch film was performed by hand. The results were promising, particularly because of the improved silage quality, even though it was evident that two things were missing: a stretchable film suitable for wrapping bale silage and a machine capable of wrapping round bales in the field that could be attached to a tractor. As far as the film is concerned, by 1984, IPG, working in close collaboration with resin producers, had developed a suitable product for the application: “Silawrap,” which was resistant to UV degradation, strong, and very tight because it was very adhesive. However, the development of the machinery posed a greater problem, and the 50 wrapping machines imported into Europe from Australia only produced mediocre results, which led IPG to offer the Norwegian company Kverneland-Underhaug the right to produce equipment under the name “Silawrap.” The performance of the new Kverneland machines has proved their worth and has overcome all the problems (Anonymous, 1996).

Even though it has become a very popular technique in many countries, the stretch PE wrapping system has shown some limits with regard to sealing efficiency (Jacobsson et al., 2002), in particular regarding the high permeability of the stretch film to oxygen (Borreani and Tabacco, 2008, 2010) and the nonuniform distribution of the plastic film between the ends and the curved surface of the bale (Borreani et al., 2007a).

The importance of stable anaerobic conditions for any silage-making system is unquestionable (Woolford, 1990; Wilkinson and Davies, 2013) and LDPE films, which are usually used as a barrier against air infiltration in both horizontal silos and in wrapped bales, only seem to work partially, especially for longer conservation periods than 6 months (Borreani et al., 2007b; Borreani and Tabacco, 2008). Since the 1990s, the only way of reducing film permeability to oxygen has been to increase the thickness of the film, which has led to an increase in costs and difficulties in managing thicker films. In 1992, Daponte proposed the use of coextruded barrier films to seal silage, but at that time plastic manufacturers had no commercial interest in producing these more expensive films. In 1996, a plastic film manufacturer in northern Italy produced a prototype of a new coextruded barrier film (Silostop 2-gamma, Mondovì, Italy) with PA as a barrier polymer to cover bunker silos (Borreani et al., 2014). The results of studies on this alternative system (based on a transparent 45 μm thick film, Silostop two-step, or on a black-and-white 125 μm thick film, Silostop one-step) on grass and

maize silages have shown positive and negligible effects on DM losses and visible top surface molds. [Borreani and Tabacco \(2008\)](#) and [Borreani et al. \(2013a\)](#) also observed an improvement in aerobic stability when oxygen barrier (OB) films were used, as they led to a reduction in aerobic and anaerobic spores in peripheral areas of the silo and during aerobic stability tests. The multilayer, coextrusion blowing technologies currently used for plastic film manufacturing, using OB polymers in combination with LDPE, allow oxygen impermeability to be increased to values that can only be achieved by LDPE films that are thicker than 2000 μm .

Plastic Films for Horizontal Silos

In recent years, several large and medium farms throughout the world have preferred bunker or stack silos, due to the relatively low construction costs and high filling and unloading work rates ([Savoie and Jofriet, 2003](#)). Once the bunker silo is filled to a desired height, the forage should be sealed with a plastic film. Several factors can affect silage DM and nutritional losses during conservation and feed out, such as the daily feed-out rate ([Mahanna and Chase, 2003](#)), the use of silage additives and the fermentation profile ([Weinberg and Muck, 1996](#)), the type of plastic sealing ([Savoie, 1988](#); [Borreani et al., 2007b](#)), the DM content at ensiling, the particle size, the filling rate, and the pack density in the silo ([Johnson et al., 2002](#)). In a 1000 t horizontal silo (12 m wide, 32 m long, and 3.7 m height), more than 25% of the initial mass is within the top meter of the silage mass ([Bolsen, 1997](#)). Leaving the silage uncovered determines an average 47% and 11% total loss of organic matter (OM) in the upper 0.5 m and in the next 0.5 m below, respectively ([Bolsen, 1997](#)). Covering with LDPE film reduces the total OM losses to 20% and 5% in the upper 0.5 m and in the next 0.5 m below, respectively. A proper sealing cover is therefore essential to reduce losses of highly digestible DM ([Bolsen et al., 1993](#)), the possible production of mycotoxins ([Cheli et al., 2013](#)), and the growth of pathogenic species ([Ivanek et al., 2006](#); [Spadaro et al., 2015](#)), which make silage less palatable and produce metabolic disorders in dairy cows. DM losses in the 0.9 m layer immediately below the PE plastic film can exceed 30% of the original ensiled crop ([Borreani et al., 2007b](#); [Holmes and Bolsen, 2009](#)). Therefore, the quality of the plastic film becomes a key factor since silages are stored in farm silos for periods of up to 12 months.

The importance of a uniform, high-quality silage over the whole profile of the silo has recently been pointed out by several researchers (Muck, 2013; Wilkinson and Davies, 2013). Good microbiological quality throughout the whole silo face can be obtained by increasing the silage density through compaction during the filling of the silo (Muck and Holmes, 2000), by planning the silo size to obtain a correct daily feed-out rate, which depends on the season and latitude (Borreani and Tabacco, 2012a), by properly sealing and covering the silo to avoid oxygen penetration during the conservation phase (Borreani et al., 2007b; Bernardes et al., 2012), by using a *Lactobacillus buchneri*-based inoculant to address silage fermentation and increase aerobic stability of the silage (Kristensen et al., 2010; Tabacco et al., 2011), by weighing down the cover to hold it tightly in place and to maintain contact between the plastic film and the silage (McDonell and Kung (2006), and by reducing the risk of mechanical damage to the cover by protecting it with a net or tarpaulin sheet.

Therefore, an ideal film to cover silage should have high mechanical properties (puncture resistance, tear resistance) to resist wind, hail, frost, and handling; from 45 to 200 μm thickness; have high impermeability to oxygen (full anaerobiosis is necessary); have physical strength properties that can be maintained over a long time period (longer than 1 year) in a natural rain- and sun-exposed environment; have UV protection (different degrees of protection in relation to the latitude); and have costs related to the necessary quality requirements (not the lowest cost).

Pitt (1986), who calculated the DM losses due to oxygen infiltration in silage, suggested that the PE covering a silo played a role in silage oxygen infiltration, due to the relatively high oxygen permeability of LDPE films. Since the 2000s, the only way of reducing film permeability to oxygen has been to increase the thickness of the films and, for this purpose, Savoie (1988) calculated DM losses due to LDPE film permeability in relation to film thickness and reported losses of 24.4 g kg^{-1} DM to 3.2 g kg^{-1} DM per each 30-day period of conservation for a film thickness that increased from 25 to 200 μm . Much of the silage stored in horizontal silos is exposed to air and it is prone to spoilage, especially in the upper part near the walls, which are difficult to seal properly (Ashbell and Lisker, 1988). Exposure to oxygen is a major cause of DM losses and silage deterioration. Oxygen supports the presence of aerobic organisms that readily use the available carbohydrates and organic acids of fermentation in forage as energy sources, thus depleting the energy of the silage cows use to produce milk and the

stability due to the acidic environment. When the sealing of the silo is not airtight, air can penetrate the silage and aerobic microorganisms can multiply, thus resulting in aerobic deterioration. Yeasts that metabolize lactic acid are the primary spoilage microorganisms in corn silage, although acetic acid bacteria and molds can also cause spoilage (Pahlow et al., 2003). Lindgren et al. (1985) reported that oxygen diffusion during storage seemed to be important for the establishment of lactate-utilizing yeast, and the adoption of a 100 μm PE cover resulted to be unable to prevent the diffusion of oxygen in bunker silages. Today, the preservation of farm silages usually takes place in bunker silos covered with 150–200 μm thick LDPE films.

Snell et al. (2002) evaluated the effect of the color (white, green, or black) and thickness (90, 125, 150, or 200 μm) of LDPE films on corn silage preservation for 34 and 104 days of conservation. They did not find any differences in any of the chemical characteristics of silage for the different thicknesses and colors of the plastic film in their study. Savoie (1987) measured the alterations in the physical strength properties of five commercial LDPE plastic films with different thicknesses (from 96 to 192 μm), four of which were black and one was white (96 μm), after 10 months of farm use in La Pocatiere, Quebec, Canada (latitude 47°21'N). He found that the resistance of the film to free-falling dart impact increased with the increasing thickness of the new film, while a decreased value of 14.9% was observed for the black films and of about 5.4% for the white one after outdoor use (Fig. 9.3).

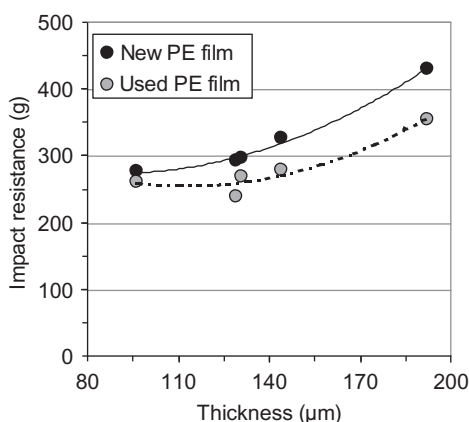


Figure 9.3 Impact resistance of new and used polyethylene film determined by the free-falling method. Adapted from Savoie, P., Physical alterations of polyethylene film used to cover silage. *Appl. Eng. Agric.*, 1987, 3, pp. 145–147.

The color of a film has been found to influence the absorption of solar radiation and consequently the temperature of the film during the day. Film stability over a long period is related to the latitude and the weather conditions of the location where it is used. The maximum solar radiation at sea level throughout the year on a clear day for different locations at latitudes ranging from 24°N to 60°N are reported in [Fig. 9.4](#). It is clear that the cumulated stress to plastic film is greater at lower latitudes, especially in the winter–spring period, while it is high at all latitudes in June and July. In the plastic community, radiation is usually measured in Langley, where $1 \text{ Ly} = 1 \text{ cal/cm}^2 = 41.84 \text{ kJ/m}^2$. Thus, the amount of energy transmitted to a piece of plastic in 1 year of continuous outdoor use ranges from 2900 MJ/m² per year in Sweden to 9100 MJ/m² per year in Saudi Arabia. Each polymer has maximum sensitivity for bond dissociation in the UV region from 290 to 400 nm. Polypropylene has three maxima, that are at 290–300, 330, and 370 nm; PA from 290 to 315 nm; and PE from 300 to 310, and at 340 nm ([Cámara et al., 2014](#)).

For these reasons, several methods are used to cover silages. These range from a single plastic film (one step) to two layers (two steps) with a thin new plastic film close to the silage and a thicker film or net to protect the under sheet. The most common films and nets utilized to cover silages and to protect silo walls are reported in [Table 9.4](#). The necessity of having a continuous barrier against air has led to changing from a one-step cover to a two-step cover or even more. The reason for the sheet being close to the silage is that, in this way, the best OB is obtained. The upper film or net is used to protect the underfilm from physical damage (wind, birds, rodents, cats, hail, etc.) and from UV damage. In recent years, several attempts have been made to develop protective systems that would avoid the necessity of using heavy objects, such as tires, soil, sand, or gravel.

Stretch Films for Wrapped Bales

Storing silage in wrapped bales has become a very popular technique in many countries ([Wilkinson and Toivonen, 2003](#)), as it offers advantages over hay production, as it is less weather-dependent, and as it offers greater flexibility in ration formulation ([Savoie and Jofriet, 2003](#); [Shinners et al., 2009](#)). Baled silage is often made from herbage that has been wilted more extensively than conventional bunker silage, as it reduces the number of bales per hectare, the plastic consumption, and

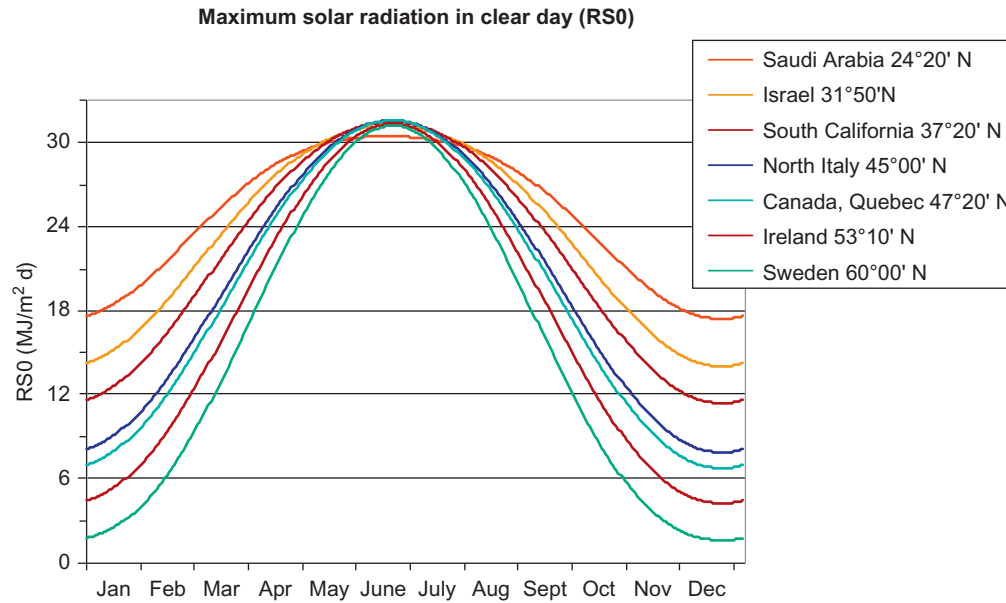


Figure 9.4 Maximum solar radiation during the year on a clear day at different locations in the northern hemisphere.

Table 9.4 Covering Typology in Relation to the Plastic Film Utilized

Type	Polymer	Film Thickness	Film Width (m)	Film Color	Oxygen Permeability (at 23 °C and 1 bar) (cm ³ /m ² /24 h)
One-step Systems (Only One New Film)					
Traditional film	LDPE	80–200 µm	4–18	Black; green; white; white/black; green/black; green/white	890–3550
OB	LDPE-PA	100–120 µm	4–8	White/black	150–400
HOB	LDPE-EVOH	100–120 µm	4–8	White/black	9–19
Two-step Systems (One New Film Close to Silage Mass Plus One Film (Traditional PE) or Net to Protect Undersheet)					
Traditional	LDPE	40–50 µm	4–18	Transparent; transparent yellow	4450–3550
OB	LDPE-PA	45 µm	4–10	Transparent yellow	150–400
HOB	LDPE-EVOH	45 µm	4–10	Transparent yellow	10–19
Open net	HDPE	Net 26–220 g/m ²		Green; black	To protect under sheet from damage (reused 4 to 7 years)
Anti-UV net	HDPE	Net 190–300 g/m ²	5–15	Green	To protect under sheet from UV and damage (reused 4–7 years)
Wall film	LDPE	75–150 µm	2–6	Black; white; black/white	To protect concrete wall from corrosion, water, and oxygen ingress

EVOH, ethylene vinyl alcohol copolymer; *HDPE*, high-density polyethylene; *HOB*, high oxygen barrier film; *LDPE*, low-density polyethylene; *OB*, medium oxygen barrier film; *PA*, polyamide.

costs and can be more convenient when fed to animals (Beaulieu et al., 1993; McEniry et al., 2007), but this poses more challenges for the outcome of the resulting silage.

The bale silage technique is characterized by its unique individual-package storage system and it is based on a well-established procedure that usually consists of wilting forage to around 400 g DM/kg, baling and then wrapping it with a stretch PE film.

The plastic film is stretched, by means of a stretching unit fixed to a bale wrapper, and then wrapped around the bale. Four to six layers of PE are usually applied in two-to-three subsequent and complete rotations of the bale, with an overlap of 50% between the layers. Another system that can be used to cover round bales is the adoption of an inline wrapping machine that wraps bales, loaded end to end in a long horizontal row, using an identical stretchable film as that used on individual wrapped bales (Savoie and Jofriet, 2003). Inline wrappers use about half as much stretch film for each bale as machines that wrap bales individually.

Owing to the stretching operations, the reduced total thickness of the combined layers of stretch film on the bale side, usually 70–105 μm (four to six layers), could be expected to make wrapped bales more susceptible to oxygen ingress (Forristall and O’Kiely, 2005). Paillat and Gaillard (2001) reported that stretching to 60% reduced the thickness from 25 to 19 μm , accelerated film wear, and decreased the service life of the film by 48% on average. For these reasons, the challenge to the OB is much greater than for conventional bunker silage, because of the proximity of most of the silage to the plastic film and the thinness of the film (Forristall and O’Kiely, 2005). In order to overcome the undesirable air exchange over the conservation period, it has been suggested to apply an increasing number of plastic film layers, that is, from four to six or even eight layers (Müller, 2005; Borreani and Tabacco, 2008). However, increasing the number of layers per bale involves prohibitive increases in plastic usage and costs and increases the time needed to wrap a bale. The disposal of the additional plastic also leads to environmental concerns (Lingvall, 1995).

Traditionally, manufacturers of stretch films for bale wrapping use PE because of its suitable mechanical characteristics and low costs. Most plastic films for stretch-wrap silage production are coextruded LDPE that are 25 μm thick before being stretched by 50% (the original length of 0.50 m becomes 0.75 m after stretching) during application to the bale (Lingvall, 1995). Longer stretching is not recommended because the film would become too weak and could be subjected to

puncturing or other mechanical damages. The mechanical and physical properties of the films that are used to wrap silages are therefore key factors in obtaining high-quality silages. The characteristics of the plastic film used to wrap bale silage could be established through different certification procedures (e.g., the DLG procedures of the German Agricultural Society or SP certification of the Technical Research Institute of Sweden). According to these suggestions, an optimal stretch film for bale silage should be characterized by minimal gas permeability ($<1800 \text{ cm}^3/\text{m}^2$ in 24 h with 0.02 MPa pressure; corresponding to $<9000 \text{ cm}^3/\text{m}^2$ at 0.1 MPa pressure), high stretching capacity (with a higher elongation at break than 400%), high puncture resistance ($>10 \text{ N}$), high UV stability for a period of at least 12 months (resistance to a total radiation in a year of $2000 \text{ MJ}/\text{m}^2$, which would be suitable for countries in Northern Europe but too low for countries located below the 45th parallel north), and high adhesiveness to keep the layers together ($>0.05 \text{ N}$). Furthermore, no reclaimed components or grains (gels) should be present and the layers in coextruded films should not be separable, in order to avoid undesirable breaks of the film during the stretching and wrapping operations.

In the past few years, one of the main drawbacks of wrapped bale silage has been the excessively high oxygen permeability of PE films, especially for longer conservation periods than 6 months (Borreani and Tabacco, 2008, 2010). The low density of $0.92 \text{ g}/\text{cm}^3$ causes PE stretch films to be relatively permeable to oxygen and other gases (McNally et al., 2005). Oxygen flow through a $25 \text{ }\mu\text{m}$ -thick film of an LDPE at 0.1 MPa overpressure, $23 \text{ }^\circ\text{C}$, and 85% relative humidity (RH) is $7120 \text{ cm}^3/\text{m}^2$ per day (American Society for Testing and Materials, 1980). Frick (2004), evaluating 15 commercial stretch films that were on the market at that time, reported oxygen permeability (measured at 0.02 MPa overpressure, $23 \text{ }^\circ\text{C}$, and 50% RH and here converted to 0.1 MPa values), in the range of $3750\text{--}6100 \text{ cm}^3/\text{m}^2$ per day. McNally et al. (2005) showed that LDPE films have poorer gas barrier properties than materials with higher density, crystallinity, and orientation, as a result of extrusion processing conditions, such as blow-up ratios.

Another important factor that is often neglected is that climatic conditions could interfere with the mechanical properties of a stretch film, especially for a permeability coefficient that increases exponentially with temperature. The temperature of the stretch film influences the permeation rates of oxygen and carbon dioxide through the film, and the colors of the film influence solar radiation reflectance and consequently film temperature (Möller et al., 1999). The value of solar reflectance

measured by Möller et al. (1999) on 25 μm thick LDPE plastic films was 31%, 28%, 13%, and 4.4% for white, light-green, dark-green, and black, respectively. The film temperature measured by an infrared camera on a clear summer day at noon was 32°C, 35°C, 46°C, and 53°C, respectively. This means that, on a clear summer day, the oxygen permeability of a 25 μm -thick black LDPE stretch film may be twofold higher than that of a white stretch film of the same thickness. Daponte (1994) measured a 7.4-fold increase in permeability when the temperature of a film rose to 70°C in the sun. Frick (2004) reported up to three-fold increases in oxygen permeability for black films that reached temperatures as high as 60°C when exposed to sun, compared to the oxygen permeability of white and light-green films, which only changed slightly (Fig. 9.5).

Overall, there has been a rapid development in the wrapping bale technology over the past 15 years, with improvements in bale densities due to the use of round balers equipped with a crop cutter (Borreani and Tabacco, 2006; Müller, 2009), reductions in working times due to the use of combined baler-wrapper machines (Münster, 2001), and improvements in the uniformity of plastic distribution on the bale surface. Borreani et al. (2007a) tested a new-concept wrapper equipped

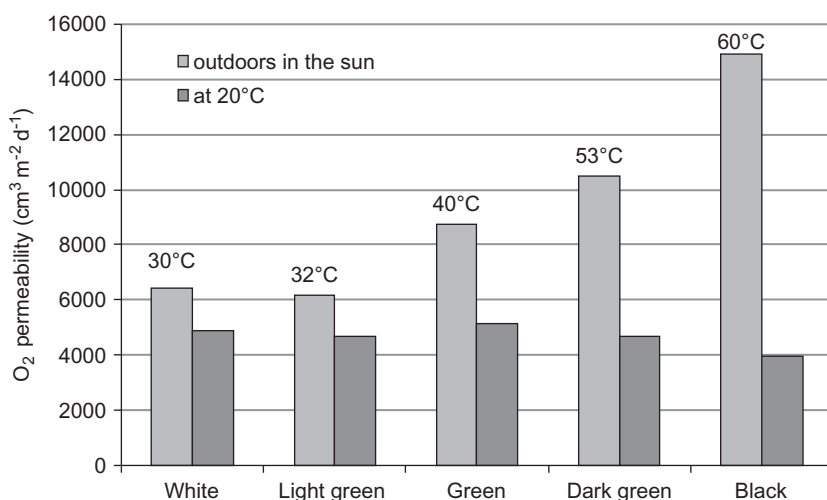


Figure 9.5 Oxygen permeability of stretchable films of different colors at 20°C and when exposed in the sun outdoors. The temperature values refer to the maximum film temperature reached outdoors on a sunny day in May in Switzerland (47° N latitude). Adapted from Frick, R., 2004. Aptitude des films d'enrubannage pour l'ensilage des bales. Rapport FAT, n. 615. Station Fédérale de Recherches en Économie et Technologie Agricoles (FAT), Tänikon, Swiss, 16 pp.

with two rotating film dispensers that allows at least seven layers to be applied over the whole bale surface with less plastic than the amount utilized by a conventional wrapper to wrap a bale in six layers.

Recently, experiments that studied the use of new-generation balers equipped with tying systems which allow a bale to be secured in the press chamber using standard net or a PE film have been set up with the aim of increasing the amount of plastic applied to the curved side of the bale (Meier, 2009). Bisaglia et al. (2011) and Tabacco et al. (2013) have shown that, with the same amount of plastic used to secure the bale with net and wrap it in four layers of stretch film, it is possible, using a 16 μm -thick LDPE tying film in the baler chamber, to obtain more than six effective layers of plastic on the curved side and on the edges of the bale, with similar costs for the plastic and better results as far as silage conservation is concerned.

However, the technological advances made in the baling and wrapping technique did not eliminate the risk of mold development on the bale surface, even with a perfect airtight plastic cover, probably because PE has a permeability to oxygen that is too high for this kind of application, and this represents a weak point of the entire ensiling system. For these reasons, many attempts have been made over the past 10 years to develop new stretchable films with the same mechanical properties as PE films, but with lower oxygen permeability, as discussed hereafter.

Other Feed Conservation Applications

With improved plastic films and better management, silage systems without a structure have proven to be a good alternative to bunker or tower silos for forage conservation (Savoie and Jofriet, 2003). From the 1970s onward, new silage systems, apart from wrapped baled silage, have been proposed in which plastic film would be the only protection for the entire outer silage surface, without any constructed wall or floor (Savoie and Jofriet, 2003). Among the alternative methods, the bag silo has become a popular storage system on a large number of farms. Crops are pressed, by the mean of a specialized bagger machine, into PE tubes made of three layers of coextruded PE, which usually range in diameter from 1.8 to 3.6 m, in length from 30 to 90 m, and in thickness from 150 to 250 μm . The use of this silo type appears to be growing rapidly due to its low cost; its flexibility of storage capacity, as it can be stored outside for a period of up to 2 years; and its ability to segregate forages on the basis of their quality (Muck and Shinnors, 2001).

Originally used to provide temporary storage for maize silage in times of excess, PE bags have proven to be effective in storing a large number of different types of moist animal feeds (chopped forages, brewer's grains, beet pulp, and high-moisture grain maize) as well as dry grain (maize, wheat, and soybean) and are being used in many countries around the world, from North and South America to Australia. The problems with harvest bag-based storage systems pertain to the difficulties of obtaining the necessary hermetic conditions for insect control, quality maintenance, and high-moisture harvesting. Appropriate levels of gas-tightness are not being achieved with the current on-farm practices and there are inherent difficulties in maintaining a sealed system for storage over several months (Darby and Caddick, 2007), with the risk of incurring high DM losses (Muck and Shinnars, 2001).

Innovative Oxygen Barrier Films for Silage Conservation

“Often when people talk about plastic films — which technically are defined as plastic sold in thicknesses of up to 250 μm — they treat them as one type of material, grouping all flexible plastic packaging into a single category. What they do not realize is that plastic films compose a broad category of materials that can be relatively simple or complex, depending on the demands of a particular product or package” (American Plastic Council, 1997). Films can be made with different resins, each of which has a unique combination of properties that makes it ideal for certain applications and can be clear or colored, printed or plain, single-layered or multilayered, and combined with other materials such as aluminum and paper (American Plastic Council, 1997). The necessary protection of feeds from air can be achieved with one layer of polymer, or where necessary, with multilayers of film, including different polymers and surface films. The barrier properties are mainly related to the ability of the films to transmit gases and vapors. Since the coextrusion of multilayer films helps to combine all the properties required for a specific application in one material, the situation is now changing rapidly, and new developments in sealing strategies have recently been reported (Borreani et al., 2007b; Borreani and Tabacco, 2014; Wilkinson and Fenlon, 2014). Among the available resins that can be coextruded with PE and which are able to greatly improve film impermeability to gasses (O_2 and CO_2), mention should be made to

PAs and EVOH, which appear to be the most promising because a layer of just a few microns of these resins coextruded with PE is able to reduce the oxygen permeability of the resulting film to a great extent. The permeance values of different polymers refer to a thickness of one micron (Table 9.5). In order to calculate the permeability of a film, the permeance should be divided by the thickness of the film (for mono-layer films) or by the thickness of the layer of the polymer with lower permeance (for coextruded films).

The recent improvements in technologies in blown film extrusion allow to finely control upto 1 μm of barrier polymer in five to nine layers and permitted higher Blow-up ratio (BUR) and longer continuous working time (Rübbelke, 2012). Furthermore, the die head ranged from 350 to 800 mm for stretch film and from 1500 to 2300 mm for film to cover horizontal silos (Personal Communication, Domenico De Angelis-Nippon Ghosei Europe). The new technologies have opened the way toward producing coextruded PE-barrier polymer plastic films to cover horizontal silos and to wrap bales. Among the thermoplastic polymers currently available on the market, EVOH offers the best barrier properties to oxygen but has been considered too rigid for coextruded films. A special grade of EVOH (SoarnoL SG611B) that combines high-barrier properties with good mechanical characteristics, such as puncture resistance, tear resistance, and stretch properties

Table 9.5 Oxygen, Carbon Dioxide and Water Vapor Barrier Properties of Polymers Useful to Produce Films to Cover Silages

Material	Permeance		
	Oxygen ($\text{cm}^3 \mu\text{m}^2 \text{ 24 h}$) ^a	Carbon Dioxide ($\text{cm}^3 \mu\text{m}^2 \text{ 24 h}$) ^b	Water Vapor ($\text{g } \mu\text{m}^2 \text{ 24 h}$) ^c
LDPE	178,000	595,000	560
HDPE	53,000	191,000	145
PP	81,000	267,000	260
PA (nylon-6)	1500	4000	4300
Polyvinylidene chloride film	80–230	320–1000	30–80
EVOH ^d	4–24	12–140	1500–3500

^aATSM D 3985–81 at 23°C, 0.1 MPa overpressure, and 85% RH.

^bATSM D 1434–75 at 20°C, 0.1 MPa overpressure, and 0% RH.

^cATSM E 96–66 at 38°C, 0.1 MPa overpressure, and 90% RH.

^dDepending on the grade of the ethylene content, higher values for 44 mol%.

(Borreani et al., 2011), has been available since 2006. These characteristics make it suitable for the production of film for agricultural applications through blown coextrusion with polyethylene to produce 20–200 μm -thick plastic films (Borreani and Tabacco, 2014). EVOH combines the excellent barrier properties of polyvinyl alcohol to oxygen with those of PE against water (Mark, 1985). EVOH-coextruded barrier films (such as the seven-layer structure PE/PE/Tie/EVOH/Tie/PE/PE) have permitted oxygen impermeability to be improved to values of below $10 \text{ cm}^3/\text{m}^2 \times \text{day}$ at standard conditions, without compromising the high mechanical performances of the PE-based films, thanks to the synergy of the polyethylene matrix (Borreani and Tabacco, 2014). The second class of polymers used for coextrusion with PE is PA, which have good thermal stability and an oxygen permeability that is about 30 times greater than that of EVOH. EVOH and PA polymers are also characterized by the absence of chlorine in their molecules, thus reducing the risk of dioxin production if they are burned. As far as the cost of using these new polymers in film silage technology is concerned, it should be emphasized that a film containing PA or EVOH is 30–50% more expensive than one made of LDPE alone at an industrial level, due to the higher costs of these polymers, to the more expensive equipment needed to process them, and to the limited economic value of the scraps generated during the manufacturing process in blown film (Kolbasuk, 2008). Although the costs of the new films are around 50–60% higher than those of commercial PE films, the cost-saving in farm applications results from the need to use less plastic than commercial PE, with a great improvement in the microbiological silage quality and a reduction in the DM losses (Borreani and Tabacco, 2014; Wilkinson and Fenlon, 2014). Recyclability of edges trims and scraps of high-barrier film with EVOH is a reality and is already a common procedure in the food-packaging industry since many years; same technology and procedure can be applied in the production of agricultural films allowing reduction of costs with minimal impact on film properties. Such possibility is given by a special additive which, blended with scraps containing EVOH, allows the EVOH to become compatible with the polyethylene, resulting in minimal effect on mechanical properties even in case of thin films (De Angelis, 2014).

Oxygen Barrier Films for Horizontal Silos

Since the oxygen impermeability of the plastic films utilized to seal silage have an important effect on reducing the top spoilage losses, it is

crucial to optimize the mechanical characteristics, together with the level of oxygen impermeability of the plastic films. The first trials with barrier film (OB) to cover horizontal silos were made with a coextruded film with PA as a barrier polymer for both 45 μm (Wilkinson and Rimini, 2002) and 125 μm (Borreani et al., 2007b) thicknesses. These first studies demonstrated the need to reduce oxygen permeability below $100 \text{ cm}^3/\text{m}^2 \times \text{day}$ (at standard conditions 23°C, 0.1 MPa, and 85% RH) to obtain a remarkable reduction in DM losses when those films were used to cover Italian ryegrass and maize silages, respectively. When PA is utilized as a barrier polymer, a PA thickness of at least 14 μm should be applied in the coextruded film to obtain an oxygen permeability below $100 \text{ cm}^3/\text{m}^2 \times \text{day}$, which is about 90% lower than the values observed for the thicker, commercially available PE film. This value provides a safety margin to overcome the problems related to changes in temperature of the film exposed to sun in farm conditions throughout the world, which cause cyclic gas-flow patterns due to fluctuations in temperature and atmospheric pressure between the inside and the outside of the silo cover (Sundeberg and Thylén, 1993). This first generation of OB film showed good mechanical characteristics, compared to commercial LDPE films of the same thickness, even though they appeared to be more rigid than LDPE films, especially when the thickness of the film was reduced to around 50 μm (De Angelis, 2012). Furthermore, some farm experiences with 45 μm -thick PE/PA OB films reported problems of fragility of the film, which in turn resulted in problems when the film was handled during silo-covering operations and this led to the necessity of protecting the film not only with a tarpaulin sheet but also with another plastic film (two-step covering system) to avoid the risk of damage during conservation. Borreani et al. (2014) provided evidence that enhancing impermeability of the silo cover to oxygen contributes to a reduction in the yeast count and to an increase in the aerobic stability of maize silage. Furthermore, the positive interaction between the length of storage and the increased anaerobiosis of silage during conservation provided by an OB film, compared to a PE film, was shown to further contribute to reducing aerobic instability and constraining DM losses in the parts of the silo that are more at risk to spoilage.

These very promising first trials led to the next generation of HOB films (Borreani and Tabacco, 2012b). In the first decade of 2000s, several commercial farms throughout the world gathered evidence about the importance of coupling improved impermeability to oxygen with the mechanical performances of plastic films to cover horizontal silos,

in order to minimize the risk of accidental damage to the cover when placing it on the herbage at the end of silo-filling and during conservation. The HOB film was made by coextruding a layer of a special grade of EVOH between two layers of PE linked to two tie layers in a five-to-seven-layer coextruded film (Borreani and Tabacco, 2014). The EVOH layer improved the oxygen impermeability of the HOB film by about 10-fold, compared to the first generation of OB films. The mechanical characteristics of the coextruded HOB film were similar to those of the PE film but were notably improved compared to OB films (Table 9.6). This improvement was due to the new EVOH formula, which makes the film particularly soft at ambient temperature, and to the reduced thickness of the EVOH layer (from 2 to 3 μm) (Borreani and Tabacco, 2014).

The evidence of the increased shelf life of silage after exposure to air, due to the use of an OB film, has been reported for both laboratory silos (Dolci et al., 2011) and farm-scale silos (Borreani et al., 2007b; Orosz et al., 2013; Borreani and Tabacco, 2014). These trials reported that corn silage in the upper layer under an OB film had a lower yeast count and greater aerobic stability than silage stored under a conventional PE film. The increased aerobic stability and a lower yeast count in the upper layer of the silage, stored under an OB film, have been attributed to reduced oxygen permeation through the silo seal during the

Table 9.6 Characteristics of the First-generation Coextruded OB Films and of the Next-generation Coextruded OB Films (HOB)

Characteristics ^a	PE	OB	HOB
Nominal thickness, μm	200	125	130
Oxygen permeability at 20°C, cm^3/m^2 24 h at 0.1 MPa and 65% RH	846	99	8.8
Force at break (N)	16	—	21
Elongation at break MD, %	601	—	1113
Elongation at break TD, %	1381	—	1176

^aHOB, high-barrier film-coextruded PE-EVOH; MD, machine direction; OB, medium barrier film coextruded PE-PA; PE, standard polyethylene film; TD, transverse direction.

Adapted from Borreani, G., Tabacco, E., Cavallarin, L., 2007b. A new oxygen barrier film reduces aerobic deterioration in farm scale corn silage. *J. Dairy Sci.* 90, 4701–4706; Borreani, G., Tabacco, E., 2014. Improving corn silage quality in the top layer of farm bunker silos through the use of a next-generation barrier film with high impermeability to oxygen. *J. Dairy Sci.* 97, 2415–2426.

storage period (Wilkinson and Davies, 2013). Borreani and Tabacco (2014) reported that a delay in the onset of aerobic deterioration in the silage under the HOB film resulted in lower DM losses and a lower amount of spoiled silage that had to be discarded, at the time of silo consumption, to avoid critical contamination of the ration in the feed mixer. This led to a net gain when a HOB film was utilized, due to the increased DM recovery and reduced labor time required to clean the top layer daily. The economic return calculated by Borreani and Tabacco (2014) for the two studied farms, where a HOB film had been used instead of a PE film, was directly related to the amount of DM ensiled and was on average €2 for each ton of fresh matter ensiled. These results are slightly lower than those reported by Bolsen et al. (2012) who, estimating the economic benefit of two sealing methods (standard PE versus OB films), calculated that the use of an OB film to cover silage would save more than €4.50 per ton of ensiled DM compared to a PE cover.

Wilkinson and Fenlon (2014), in their review paper on the use of OB films to cover silage, analyzed 41 trials conducted throughout the world in which OB films were compared with commercial PE films. The losses from the top surfaces of the bunker and in clamp silo experiments are reported in Fig. 9.6, and the length of each line shows the

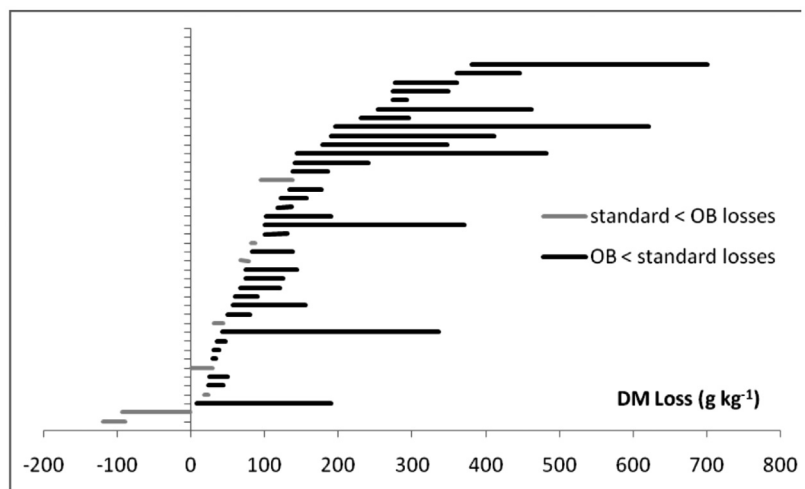


Figure 9.6 Bunker and clamp silo comparison and differences (standard PE–OB film losses of DM) ordered by OB loss. Adapted from Wilkinson, J.M., Fenlon, J.S., 2014. A meta-analysis comparing standard polyethylene and oxygen barrier film in terms of losses during storage and aerobic stability of silage. *Grass Forage Sci.* 69, 385–392.

difference between the two films. The black lines indicate lower losses for the OB film and the gray lines indicate the opposite. Only 2 out of 41 trials showed greater losses for OB films than for PE films. Although the data are quite variable, it can be observed that the frequency of large differences between the types of sealant films tends to increase as the overall level of loss increases.

Oxygen Barrier Stretch Films for Wrapped Bales

Recent farm survey conducted to establish the incidence of fungal growth on baled grass silage in Ireland has shown that up to 90% of the bales examined had visible fungal growth (O'Brien et al., 2008). Furthermore, in a temperate environment, Borreani and Tabacco (2010) observed that the development of molds in the peripheral areas of the bale could involve more than 10% of the bale surface, when the conservation period has been longer than 5 months. Even though the baled silage system is based on a well-established procedure, the fact that the incidence of mold spoilage can be relatively high (O'Brien et al., 2008; Borreani and Tabacco, 2010) suggests that the current baled silage-making practices should be considered only partially satisfactory (McEniry et al., 2011). Although the usual recommendation to farmers is to use six nominal layers of stretch film to provide a valuable safety margin, many authors (Lingvall, 1995; Keller et al., 1998; Paillat and Gaillard, 2001) have demonstrated that, when using commercial PE stretch films, the amount of oxygen that diffuses into the bale during storage and consequently the amount of visible molding that occurs can only be reduced by applying more film layers, but, as previously stated, this requires more wrapping time, as well as an increase in costs and environmental concerns. The penetration of air into silage results in DM and nutrient losses, the accumulation of pathogens and mycotoxins, and a reduced DM intake. For these reasons, great efforts have recently been made to reduce the possibility of air ingress through the plastic cover during the conservation period, in order to overcome the lack of OB of the PE film, without increasing the amount of plastic used per tonne of stored DM. Improving the oxygen impermeability of the stretch film has thus been identified as one of the most effective ways of obtaining significant improvements in the conservation quality of baled silage. New plastic-manufacturing technologies, coupled with new low oxygen permeability polymers that can be coextruded with PE, offer the possibility of producing multilayer stretch films

for the wrapping of bale silages at costs that are competitive with those of the conventionally used PE on farms (Borreani and Tabacco, 2005). Furthermore, these new films could solve the problems that have restricted the application of wrapping technology to silage with a lower moisture content than 400 g/kg (Borreani and Tabacco, 2008; Borreani et al., 2009).

A first attempt at using coextruded OB stretch wrap films with baled silage was described in detail by Borreani and Tabacco (2005, 2008). This first generation of OB stretch wrap film was developed by the coextrusion of LDPE with PA. The results showed an evident effect of the film type and number of layers on the percentage of bale surface covered by mold, with lower values than 15% in the bales wrapped with at least four layers of OB film conserved for longer periods than 8 months. Storage DM losses were also affected by the type of film that was used and by the number of layers applied, with consistently lower values in OB silages for at least four layers of film (Borreani and Tabacco, 2008). It was concluded that the new stretch film could be used to conserve silage for more than 8 months, without any decrease in the conservation quality or prohibitive increases in costs and plastic usage.

Further improvements in oxygen impermeability of films used for covering bunker silage were obtained by coextruding a thicker layer than 2 μm of a special grade of EVOH between two or more layers of PE (Borreani et al., 2009). The oxygen impermeability of the new HOB film was improved by about 21- and 374-fold, compared to that of first generation of OB and standard PE films, although it maintained similar mechanical properties than those of the best-performing PE stretch film (Table 9.7).

When tested in research trials performed at a farm-scale, the HOB stretch films with improved oxygen impermeability were effective in reducing the DM losses during conservation to values of around 2% in alfalfa baled silage at a DM content ranging from 550 to 650 g/kg (Fig. 9.7). Other authors have reported DM losses of 6% (Hancock and Collins, 2006), and 7% of the total harvested DM (Shinners et al., 2009; Borreani and Tabacco, 2008) for alfalfa baled silage at similar DM contents and wrapped with standard PE stretch films. The improved oxygen impermeability has also had a remarkable influence on the evolution of the surface covered by mold: the higher the barrier properties of the plastic film utilized to wrap the bales, the greater is the reduction in mold growth on the bale surface over the conservation period (Fig. 9.8).

Table 9.7 Characteristics of Three Stretch Films with Different Oxygen Impermeability. The Measurements were Conducted on New Film Before Stretching

Item	Plastic Film		
	PE	OB	HOB
Thickness (μm)	25	25	25
Oxygen permeability at 23°C ^a	7120 ^b	408	19
Oxygen permeability at 50°C ^a	21,360 ^b	2062	45
Puncture resistance to probe penetration (mm)	20.8	12.4	16.7
Force at break (N)	6.4	5.4	6.2
Energy to break (J)	0.08	0.03	0.07
Tensile strength at break, MD (MPa)	62.0	34.1	34.5
Tensile strength at break, TD (MPa)	37.6	23.2	22.9
Elongation at break, MD (%)	534	425	716
Elongation at break, TD (%)	1015	497	942

MD, machine direction; TD, transverse direction.

^acm³/m²/24 h at 0.1 MPa and 65% RH.

^bFrom the barrier database.

Data from Borreani, G., Tabacco, E., 2010. Use of new plastic stretch films with enhanced oxygen impermeability to wrap baled alfalfa silage. Trans. ASABE 53, 635–641.

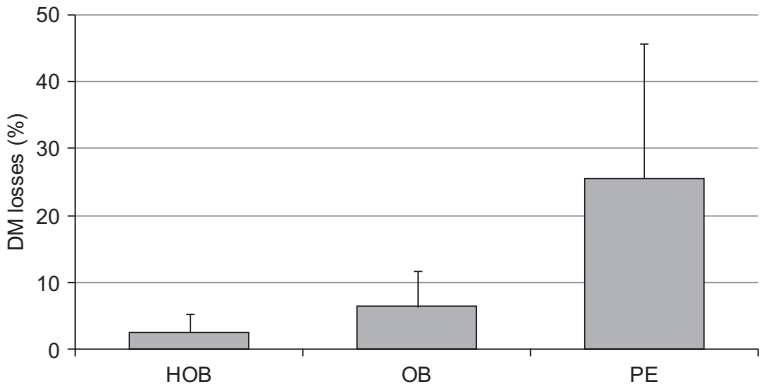


Fig. 9.7 DM losses in relation to oxygen impermeability of stretch films in alfalfa baled silages after 420 days of conservation (average of three trials in Northern Italy). Adapted from Borreani, G., Tabacco, E., 2010. Use of new plastic stretch films with enhanced oxygen impermeability to wrap baled alfalfa silage. Trans. ASABE 53, 635–641.

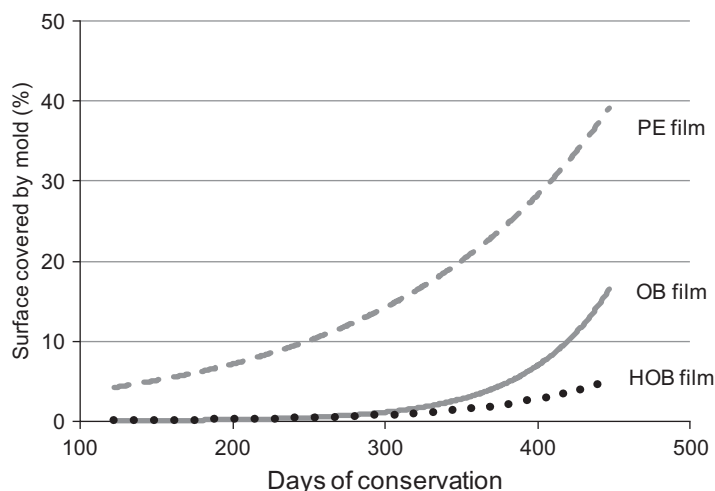


Figure 9.8 Surface covered by mold in relation to days of conservation in alfalfa baled silage wrapped with three stretch films differing in oxygen impermeability. Adapted from Borreani, G., Tabacco, E., 2010. Use of new plastic stretch films with enhanced oxygen impermeability to wrap baled alfalfa silage. *Trans. ASABE* 53, 635–641.

Owing to the possibility of using less plastic and a lower number of layers on the bale surface, the next research steps shall be focused on establishing bale management tips which could provide greater protection from mechanical damage and reduce the risk of plastic puncturing during handling and conservation (which currently can only be provided by increasing the amount of plastic applied).

New Perspectives of Bioplastics on Livestock Farms

In recent years, a great deal of attention has been paid to the search for cost-effective alternatives to replace petroleum-based commodity plastic films to cover silages, such as biodegradable materials with competitive mechanical properties (Borreani and Tabacco, 2015). Some agricultural plastic films may be intrinsically difficult to recycle, since they are usually contaminated by soil, sand, silage, and other organic residues (Holmes and Springman, 2009). The disposal of PE sheeting could represent a potential environmental concern, because it is nonbiodegradable, difficult to recycle, and it can basically only be used once (Kyrikou and Briassoulis, 2007). Bhatti (2010) reported that agricultural plastics in the United States are rarely disposed correctly. The current

disposal methods include dumping at a solid waste transfer station, leaving them in the fields, and plowing them into the ground. Furthermore, it has been reported that some farmers throughout the world burn plastic films in an open fire on their farms (Holmes and Springman, 2009; Bhatti, 2010; Borreani et al., 2013b). These plastics, when burned under uncontrolled fire conditions at low temperatures, release toxic volatile compounds, thus resulting in human and environmental exposure (Font et al., 2004). Furthermore, the cost of producing virgin materials is sometimes considered less than the cost of collecting, cleaning, sorting, and processing postconsumer plastics (Briassoulis et al., 2013).

An alternative way of disposing agricultural plastic wastes is through biodegradation. Most experts define a fully biodegradable polymer as a polymer that can be completely converted, by microorganisms, into carbon dioxide, water, minerals, and microbial biomass, without leaving any potentially harmful substances in the environment (Kyrikou and Briassoulis, 2007). Biodegradable bioplastics are derived from biological sources, instead of petroleum, and are increasingly being used as an alternative to petroleum-based plastics (Momani, 2009). Bioplastics come from a wide range of sources, but many plant-based bioplastics are derived from food crops, including starch (maize and potatoes) and oleaginous plants (rapeseed and sunflower). A wide variety of bioplastics exist but only a few have been put into major commercial production (Momani, 2009). A starch-based polymer, also known as Mater-Bi (MB), is the first completely biodegradable and compostable biopolymer ever invented (Bastioli, 1998), and it has recently been shown that it can be utilized to produce films of different thickness that might be suitable for covering silage (Borreani et al., 2010). Other alternatives to biodegradable plastic films to cover silage, that is, biodegradable coatings such as straw, apple pulp, or food industry waste, have been studied and suggested to replace PE films (Brusewitz et al., 1991; Savoie et al., 2003), but until now these materials have been unsuccessful in forming a stable barrier against air and the environment for longer periods than 1 month (Brusewitz et al., 1991; Savoie et al., 2003; Denoncourt et al., 2007).

In 1953, an anonymous author questioned whether concrete or woody tower silos could be replaced by plastic film, and this led to the era of plastic bunker silos (Gordon et al., 1961). Nowadays, the question is whether it is time to introduce bio-based biodegradable films as an alternative to plastic films to cover silage. Researches have shown that the bacteria and fungi which inhabit agricultural soil and mature

compost have a great capability of degrading MB (Accinelli et al., 2012). The availability of new biodegradable polymers derived from different sources and the improved mechanical properties of the resulting films have opened a new scenario in the management of bunker silo coverings. Borreani et al. (2010), in a preliminary study, showed, for the first time, that biodegradable film could be a promising alternative to cover silages for conservation periods as long as 4 months, and the results of this research suggested a thickness of at least 120 μm to avoid degradation of the plastic film within a few months. This first experiment (Borreani et al., 2010) led to the development of a new blend, derived from renewable sources, which in turn led to the production of blown films to cover silage. These films have been improved as far as the stability to microbial activity over time is concerned and have an oxygen permeability that is 42% lower than commercial PE films of the same thickness. The main objective of developing a new biodegradable plastic film to cover silage is to have a film that is stable to microbial and hydrolysis activities for longer periods than 8 months under natural rain- and sun-exposed conditions, coupled with a high impermeability to oxygen (Borreani and Tabacco, 2014).

Borreani and Tabacco (2015) have evaluated two new bio-based biodegradable plastic films to cover silages so as to establish their performances in indoor conditions and to obtain guidelines in order to develop new biodegradable films for farm-scale experiments. A characteristic that greatly diversified these new films from the PE films was the water vapor transmission rate, which was 10-fold greater in the MB films than in the PE films. The greater permeability to water vapor of the biodegradable films than the PE ones increased the DM content of the silages in the uppermost layer close to the film, whereas it did not affect the fermentation profile. The whole mass of the silages covered with the biodegradable bio-based films showed similar fermentative profiles to those conserved below the PE films. The promising results obtained by Borreani and Tabacco (2015) indicate that it could be possible to develop new degradable materials to cover silage. Biodegradable plastic films have proved to work well for longer conservation periods than 5 months in indoor conditions (Borreani and Tabacco, 2015), but they still need to be tested in farm conditions to evaluate their ability to protect silage from the detrimental effects of molds during conservation. Therefore, further research should be undertaken to improve the biodegradable blends in order to enhance microbiological film stability over time and to evaluate biodegradable plastic films in outdoor conditions.

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10 Disposal of Plastics

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Introduction

Plastics contribute in many ways to the agricultural sector; however, after the useful life of the plastic has expired, they represent a liability. Plastic polymers, in their many forms, have been rapidly adopted by the agricultural sector since their introduction in the mid-20th century. Current estimates of annual worldwide plastic production are some 300 million tons. About 4% of the plastic produced in Europe and the United States, or 4.6 million tons, is used each year in the agricultural sector (Briassoulis and Hiskakis, 2012; PlasticsEurope, 2013). Plastics in agriculture are generally classified in two broad categories: containers and films. Plastic film products are less rigid than plastic container products.

Agricultural films are used in both the horticultural sector and the grain crop and dairy sectors. Examples of plastic film include bale wrap, tubing, bale netting, bunker silo covers, high tunnel covers, low tunnel covers, and plastic mulch. Films are primarily low-density polyethylene (LDPE) but can also be polypropylene (PP).

Agricultural containers are primarily high-density polyethylene (HDPE) but can also be polystyrene (PS) or PP. Examples of rigid plastic in agriculture include containers, carboys, greenhouse trays, and pots.

Unfortunately, most plastics used in agriculture are not reusable. Nearly all plastics in agriculture must be disposed of after a single use (e.g., containers of concentrated pesticide), at the end of a single growing season (e.g. plastic mulch film) or calendar year (e.g. bunker silo covers).

There is no single solution for the disposal of plastic. Disposal options vary based on geographical location, application, and plastic types. Indeed, if one were able to fix these three parameters, the disposal options are still likely to change based on volatility in the recycling market related to the price of petroleum.

After the useful life of plastics used in agriculture, there are three general pathways to consider for their disposal: recycling, energy reclamation, and landfilling. These options are not always available to all producers of waste plastic.

Recycling

There are four categories of plastic recycling: primary, secondary, tertiary, and quaternary (Ehrig, 1992; Fisher, 2003; Harper, 2002). Primary recycling is the creation of similar quality products from the recycled source. Secondary recycling is the creation of products from the reclaimed material with less demanding specifications, such as the creation of composite lumber from waste plastics. Tertiary recycling is the use of a recycled product as a chemical raw material. Finally, there is quaternary recycling, which some do not consider recycling. Quaternary recycling is the incineration of a plastic to reclaim heat energy. Both tertiary recycling and quaternary recycling will be discussed in later sections.

Primary recycling of agricultural plastics is difficult for a number of reasons. Contamination, the presence of nonplastic material in the used plastic, is the most significant roadblock to primary recycling. Nearly all plastics used in the agricultural sector are in contact with dirt, plant matter, chemical residues, and are exposed to the elements during its useful life.

The extent of contamination on agricultural plastics can vary widely as they are retrieved from the field. Application, contaminant density, plastic type, and collection methods can all affect contaminant levels. Plastic film pulled directly from the raised beds has a contamination level ranging from 4% to 66% (Brooks, 1997; Hussain and Hamid, 2003). Film plastics used in the horticultural sector for greenhouse coverings and low tunnels have less contaminants, but the level can be up to 50% by weight (Briassoulis and Hiskakis, 2013). Concentrations this high will certainly exclude the recovered plastic from the primary recycling market. The amount of plastics that accumulate no debris or other contaminants from the aforementioned applications in agriculture is negligible. Thoroughly washing the used agricultural plastics would prepare them for the primary recycling market, but the energy used to perform this negatively affects the reclaimed energy content.

In fact, even the secondary recycling market, a market traditionally more accepting of contaminated feedstock, requires a very low contaminant level. Acceptable contaminant levels for a number of primary and secondary recycling efforts are summarized in Table 10.1.

Table 10.1 Contaminant Specifications for Primary and Secondary Recyclers

Company/Entity	Recycled Products Produced	Contamination Specification
California (USA) postconsumer recycling	Film bags, containers, and composite lumber	No biodegradable materials, no trash, no loose paper, and no oil or grease
New Jersey (USA) Agricultural Recycling Program	Collected materials sold to plastic brokers/recycling market	Material must be free of all debris including plant material and soil
Recycling Ag Plastics Project, Cornell University (USA)	Collected materials sold to plastic brokers/recycling market	No mud, sod, soil, organic matter, and loose paper
TREX (USA)	Wood alternative decking products	No trash, food, or loose paper, and no moisture
CeDo Recycling (The Netherlands)	Garbage bags	Film to be swept clean, no strings, net wraps, or foreign bodies (metal and stones)
PLASTEC (Italy)	Plastic accessories for florists	Contamination levels not to exceed 1% moisture or 2% dirt by weight

Adapted from Briassoulis D, Hiskakis M. 2013. Technical specifications for mechanical recycling of agricultural plastic waste. *Waste Manag.* 33, 1516–1530.

Roadblocks to recycling are not limited to contamination. Recyclers also prefer, and in some cases require, the recovered material to be sorted by plastic type. Unfortunately, this is a process that can be difficult. Film plastic, for example, is commonly either polypropylene or polyethylene. Rigid containers may be polystyrene, polyethylene, or polypropylene. Therefore, classification by type cannot be done by sight alone.

When plastics are sorted in the municipal solid waste stream, automated, near-infrared spectroscopy optical separators are used. This technology is not employed for agricultural plastics for two reasons. First, the agricultural plastic recovered is generally baled and therefore not amenable to the sorting machine (Briassoulis and Hiskakis, 2013). Also, the collection procedures specified for agricultural plastics headed

to the recycling market require the sorting and cleaning to be done prior to entering the recycling stream, so further sorting is not required (RAPP, 2014).

Also, the market for recyclable plastic is directly affected by the global oil price (Meng et al., 2015; Triguero et al., 2014). The demand for recyclable plastic decreases as the price of petroleum decreases. This not only discourages new business models from developing related to the collection and resale of recyclable plastic, but it also discourages existing plastic manufacturers from purchasing recycled product, and it forces existing plastic collection and brokerage companies to store recycled plastic until the price of petroleum increases.

Finally, recycling is a challenge for nonpoint source materials. The rural nature of many agricultural settings increases the energy expended in transportation and collection.

Plastics have been recycled through innovative applications. Nontraditional recycling options for agricultural plastics include using the recovered material to supplement wood fiber and other natural fibers to produce eco-composites. These composites divert the plastic from landfill and incineration stream and are used as building materials and industrial products (Gonzalez-Sanchez et al., 2014; Picuno et al., 2012). An example of an eco-composite is composite lumber. This blend of recovered plastics and wood fiber is used for parking curbs, marine pylons, and residential or commercial decking, when efficient collection is possible (Najafi, 2013). However, supply far outweighs demand for the used plastics recycled in these forms, and this option exists primarily for those plastic users located near the composite lumber facilities.

Despite these many challenges, recycling rates for plastics are increasing, albeit at a modest rate (PlasticsEurope, 2013).

Energy Reclamation

Not all waste is created equal. For decades, researchers have identified plastic as a high-energy material worthy of energy reclamation effort. HDPE, LDPE, PP, and PS are hydrocarbons—products directly derived from petroleum—and as such, they have an energy density approaching fuel oil. Many potential solid fuel sources and their associated energy densities are shown in Table 10.2.

Plastic not only has a high-energy content, but it also requires energy for its production. Approximately 4% of the annual worldwide

Table 10.2 Energy Density of Various Materials

Material	Heating Value, MJ/kg (Btu/lb)
Fuel oil	48.6 (20,900)
Polyethylene	46.3 (19,900)
Polypropylene	44.1 (19,000)
Polystyrene	41.4 (17,800)
Recovered agricultural plastics	30–40 (13,000–17,200)
Tires	30.1 (13,000)
Subbituminous coal	27.3 (11,700)
Wood (pine)	22.3 (9600)
Wood (oak)	19.3 (8300)
Municipal solid waste (dry)	16.2 (7000)
Municipal solid waste (50% moisture)	7.9 (3400)

Adapted from Garthe, J., Kowal, P. 1993. Resource recovery: turning waste into energy. Penn State Agricultural Sciences Cooperative Extension, University Park, PA, USA; Gupta, A., & Lilly, D. 2003. Thermal destruction of wastes and plastics. In: Andradý, A. (Ed.), *Plastics and the Environment*. John Wiley and Sons, Hoboken, NJ, USA, pp. 629–696; Briassoulis D, Hiskakis M. 2012. Experimental investigation of the quality characteristics of agricultural plastic wastes regarding their recycling and energy recovery potential. *Waste Manag.* 32, 1075–1090 (Garthe and Kowal, 1993; Gupta and Lilly, 2003).

petroleum produced is used as chemical feedstock to create plastic and the same amount is expended in the energy required to perform this transformation through the plastic-manufacturing processes (Hopewell et al., 2009; Siddique et al., 2008).

Recovering energy from plastic takes many forms. Tertiary and quaternary recycling rates are also increasing (PlasticsEurope, 2013).

Chemical Recycling

Tertiary recycling, or chemical recycling, is the only one of the four types of recycling which conforms to the principles of sustainable development because it leads to the formation of the raw materials from which the plastics are originally made (Wong et al., 2015).

Pyrolysis is the most common form of tertiary recycling. Pyrolysis is the thermal degradation of plastic in an inert atmosphere (Demirbas, 2004; Pinto and Costa, 1999; Punčochář and Ruj, 2012). This process results in hydrocarbons which can be used in the

petrochemical industry as a feedstock or burned directly as a fuel. Energy recovery through pyrolysis may be the most suitable way to dispose of a highly mixed plastic resource like recovered agricultural plastics (Hopewell et al., 2009).

Pyrolysis is also used to produce energy in the form of combustible gas and biochar from animal manures. This process requires additional energy to sustain the pyrolysis reactor due to the high water content and low energy density of manure. If the feedstock for this process is supplemented with a mixture of 10% used agricultural plastics, the process becomes energetically sustainable (Ro et al., 2014).

The benefits of chemical recycling are clear; it is technically feasible to reconstitute recovered plastic from the agricultural sector to its original petrochemical constituents. This not only diverts plastic from the landfill but also generates useful products. Unfortunately, this process is currently not economically viable without considerable subsidies due to the comparatively low cost of petroleum (Hopewell et al., 2009).

Direct Combustion

Direct combustion, quaternary recycling, through incineration is another option for used agricultural plastics. Heat generated from plastic combustion can be used to produce steam for electrical energy generation.

High temperature combustion facilities such as cement kilns represent a potential disposal option for nonrecyclable agricultural plastics. Cement kilns represent one of the most energy-intensive consumers in the world. Most of this energy is generated through the combustion of fossil fuel sources, representing 10–15% of the total worldwide industrial energy use and resulting in 6% of the global CO₂ emissions (Uson et al., 2013).

Plastics have been targeted as a high-energy alternative fuel for cement kilns and are used in that industry. Unfortunately, much like the eco-composite recycling option, supply far outweighs demand for the used plastics incinerated in cement kilns and this option exists primarily for those plastic users located near the kilns.

There are other negative consequences of direct combustion. This is a noncyclical, nonreversible option. Direct combustion cannot be reversed. The production of energy from waste is a higher order use than landfilling, but incinerating plastic only reduces the consumption of traditional fossil fuels if it displaces their use as a fuel source.

Incineration of unsorted plastics can result in the formation of dioxin (Demirbas, 2004), so feedstock must be carefully chosen.

Landfilling

Considering the energy density of plastic and the opportunity cost of using petroleum to produce plastic, landfilling plastic after a single use is the lowest order use and the least desirable option for nonrecyclable plastic. Unfortunately, landfilling has been shown to be the lowest cost option for the private sector (Dijkgraaf and Vollebergh, 2004) and is often the only option among recycling, energy reclamation, and landfilling for many rural areas. However, in the same study the environmental cost of landfilling exceeded the incineration cost by 20%.

Increasing landfill taxes, such as those seen in the United Kingdom, and plans for outright bans on plastic in landfills by the year 2020 by other European countries will reduce and possibly eliminate this as an option for used agricultural plastic (Hopewell et al., 2009; PlasticsEurope, 2013).

In the United States, however, landfilling is still the preferred method of disposal of agricultural plastics. Taken as a whole, the 80% of the postconsumer plastic is sent to landfills. In the agricultural sector, this number jumps to about 96% (Meng et al., 2015).

Plastic has been shown to not contribute to the toxicity of leachate from landfills (Siddique et al., 2008). Further, the environmental impact from a well-managed, modern landfill is limited to the plastic collection and transport aspects of getting the plastic to the landfill site.

Reuse

Agricultural plastics are, in very limited examples, reused. Film plastics are replaced seasonally because they are degraded from exposure to the elements during the growing season, damaged and contaminated from field operations, and destroyed during their collection. Their reuse options are limited if not nonexistent.

Rigid plastics in agriculture have been widely adopted, in part, because they are durable, ostensibly resulting in their effective and common reuse. Yet, reuse is still rare by primary, high-volume users. Nursery pots, for example, lack standardization in size. This seemingly innocuous issue prevents automation for cleaning equipment in

an industry very contentious of disease prevention and pest control. Reuse is generally only considered by the end user.

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Index

Note: Page numbers followed by “*f*” and “*t*” refer to figures and tables, respectively.

A

Acrylics
 greenhouse coverings, 122
 sheets, 118–119
Additives, 4–5, 46, 120–121, 132
Aerobic organisms, 156–157
Aerobic stability tests, 154–155
Agriculture, 79
 containers, 187
 films, 56, 187
 plastics, 8
Agrotextiles, 11, 39, 42
Air temperature, 63–64
Air-pruning pots growing system,
 136–137
 girdling root, 137*f*
Airflow, 65
American Nursery Stock Standards,
 133
American Society for Plasticulture
 (ASP), 1
Amorphous materials,
 25
Anaerobic conditions,
 154–155
Animal feed storage, plastic film for,
 150–165
 other feed conservation
 applications, 164–165
 plastic development for silage
 conservation, 151–155, 152*t*
 plastic films for horizontal silos,
 155–158, 157*f*
 stretch films for wrapped bales,
 158–164

Animal production, plastics in, 8.
 See also Greenhouse
 production, plastics in
 innovative oxygen barrier films for
 silage conservation, 165–176,
 166*t*
 plastic film for animal feed
 storage, 150–165
 plastic types on livestock farms,
 145–150
 polymers on livestock farms,
 145–146
Anti-condensate films, 120–121
Aquatic landscape, 132–133
ASP. *See* American Society for
 Plasticulture (ASP)
Automated transplanting machines,
 134, 134*f*
Automation, 84, 99

B

Backflow prevention system,
 100–102
Bag silo method, 164
Bale(s), 150–151
 bale-wrap films, 145
 baled silage, 158–161
 film, 187
 wrapping, 148–149
 wraps, 150–151
Beneficial insect populations, 68–69
Biaxially oriented film, 37
Big bale forage packaging systems,
 153

- Bio-based biodegradable films, 175–176
- Biodegradable, 139
 - bioplastics, 175
 - films, 10
 - nonwoven fabric row covers, 63
 - products, 55
- Biological clogging agents, 92
- Biological pest management, 107–108
- Biomass, 140
- Bioplastics, 140–141
 - on livestock farms, 174–176
- Bi-oriented PVC, 13
- Black mulches, 52
- Black plastic mulch, 48
- Black-colored mulch, 48
- Blackberry, 70–71
- Blow-molded containers, 136
- Blow-up ratio (BUR), 166–167
- “Blown bubble” process, 46
- Blown film extrusion, 37–40, 166–167
- Blown Film Tower, 37, 38*f*
- Blown-film, 31–32, 41–43
- Blue-dye test, 95–96
- British Thermal Units (BTUs), 55
- Bunker silage covers, 145
- BUR. *See* Blow-up ratio (BUR)

- C**
- Cast film process, 34–35
- Cement kilns represent, 192
- Chemical clogging, 100
- Chemical recycling process, 191–192
- Chiller, 35–36
- “Chimney effect”, 53
- “Circling roots”, 136–137
- Citrullis lanatus*, 114
- Clay pots, 117–118, 130–131
- Clayey soil, 93–94
- Cleaner product, 53
- Climatic conditions, 162–163
- Clogging prevention, 100–101
- “Coat-hanger die”, 33–34
- Coextruded barrier films, 154–155
- Coextrusion blowing technologies, 154–155
- “Cold flow”, 27–28
- Coleman, Eliot, 71
- Color of mulch, 47–51
- Complete cover system, 149–150
- Compost application, 107–108
- Compostable, 139
 - containers, 139
- Container-grown nursery stock, 73
- Container-grown plants, 129–131, 130*f*
 - specialized growing media, 131
- Contamination, 188
- Conventional fossil fuels plastics, 140
- Corn starch, 140–141
- Covalent bonding, 24
- Cover crop, 107–113
- Cover silages, 158
- CowPots, 139
- Crop
 - crop microclimate, row covers on, 63–65
 - airflow, 65
 - light, 64
 - relative humidity, 64–65
 - temperature, 63–64
 - vapor pressure deficit, 64–65
 - cucurbit, 68–69
 - ET values, 95
 - harvesting, 84
 - planting, 67
 - row covers on
 - beneficial insect populations, 68–69
 - crop quality, 69
 - insect pests, 66–68
 - overwintering, 70–73
 - season extension and yield increases, 65–66
 - water use determination, 95

Cropping systems, 95
Cross-machine direction, 36–37
Crystalline structure, 25
Cucumbers (*Cucumis sativus*),
113–114
Cucumis melo, 114
Cucumis sativus. *See* Cucumbers
(*Cucumis sativus*)
Cucurbita pepo. *See* Summer squash
(*Cucurbita pepo*)
Cucurbits, 114
crops, 68–69

D

Deeper nursery containers, 135
Determinate cultivars, 113–114
Die in extruder, 31–33
Direct combustion process, 192–193
Direct covers. *See* Row covers
Disposal of plastics, 8, 187
energy reclamation, 190–193
landfilling plastic, 193
recycling process, 188–190
reuse, 193–194
DM. *See* Dry matter (DM)
“Double poly” greenhouse, 119–120
Double-cropping, 84
Double/triple crop, 54
Drainage, 15
Drip irrigation, 6–7, 79–80
advantages, 83–84
components of systems, 86*t*, 87*f*
disadvantages, 85
installation of systems, 85–92
drip tubing and tape, 88, 89*f*
emitters, 88–90
filtration, 92
injection and safety equipment,
91–92
tubing placement in row, 90–91
operating irrigation system,
92–103
blue dye, 96*f*
clogging prevention, 100–101

crop water use determination, 95
example, 97–98
flushing system, 102–103
injecting fertilizers, 101–102
irrigation controllers, 99
maximum water amounts, 98*t*
reusing tubing or tape, 103
soil moisture sensors, 99–100
soil water-holding capacity and
available water, 93–94
system run times, 95–97
water application uniformity,
99
origins of, 80–82
placing drip tape, 82*f*
products, 91*t*
tubing, 80*f*
uses of, 82–83
water, 79
Drip tape, 81–82, 85–88, 89*f*
Drip tubing, 85–88, 89*f*
Dry grain, 165
Dry matter (DM), 145–146

E

Eco-composite, 190
Eco-friendly growing containers,
139–140
Electrical fertilizer injector, 91–92
Emitters, 88–90
Emmert, Dr. Emery, 1, 47
Energy reclamation, 190–193
chemical recycling process,
191–192
direct combustion process,
192–193
energy density, 191*t*
Ensilage, 15
Environmental stresses, 107–108
ET. *See* Evapotranspiration (ET)
Ethylene vinyl acetate, 118–119
Ethylene-vinyl-acetate copolymer
(EVA), 3
Europe, plasticulture in, 8

European crop diversification
programs, 3
European Technical & Quality
Standards for Nursery Stock,
133
EVA. *See* Ethylene-vinyl-acetate
copolymer (EVA)
Evaporation, reduced, 52
Evapotranspiration (ET), 95–96
EVOH. *See* Vinyl alcohol copolymer
(EVOH)
Extension Educators, 2
Extension Services, 95
Extension System, 93–94
Extruder, 29–31, 30*f*
Extrusion, 28–41, 133–134
blown film extrusion, 37–40
die, 31–33
effects of differing velocities on
polymer, 32*f*
extruder, 29–31, 30*f*
film production considerations, 41
flat film
extrusion, 33–37
rolls, 35*f*
profile extrusion, 29

F

Fabrics, 62
Farming practices, 107–108
Father of Plasticulture. *See* Emmert,
Dr. Emery
Feed throat, 29–30
Feedstock, 190–192
Fertigation, 101–102
Fertilizer, 84, 101–102
injecting, 101–102
reduced fertilizer leaching, 52
Fewer weed problems, 52
Fiber-molded pots, 139
Fiberglass, 122
greenhouse, 122
Fiberglass reinforced plastic sheets
(FRP sheets), 118–119, 122

Field tunnels, 113
Film manufacturing, 4
Film plastic, 189
Filtration, 92
Flat film, 31–32, 36, 41–43
extrusion, 33–37
process, 34
rolls, 35*f*
Flat sheets, 122
Flat-roofed *parral*-type greenhouse, 9
“Fleeces”, 62
Float-bed systems, 112–113
Floating mulches. *See* Floating row
covers
Floating row cover. *See* Row covers
Florida, 95
Flushing system, 102–103
Forage conservation technique,
148–151
Forage crops, 150–151
“Free chlorine”, 100
FRP sheets. *See* Fiberglass reinforced
plastic sheets (FRP sheets)
Fruit crops, 113
Fumigation, 53

G

“Gallon nursery container”, 135–136
Game changing application, 117–118
Gas exchange, 53
“Girdling roots”, 136–137, 137*f*
Glucose, 140–141
Good agricultural practices, 16–18
Gothic structures, 111
Greenhouse production, plastics in,
117–118. *See also* Animal
production, plastics in
hydroponics, 126–127
plastic greenhouse coverings,
118–124
acrylic twin-wall greenhouse
covering, 122*f*
cutter connected plastic covered
greenhouse, 120*f*

- polyethylene covered greenhouse, 119*f*
- white poly greenhouse covering, 121*f*
- plastic pots, trays, and flats, 124–126
- Greenhouses, 7, 11–15, 108, 113
 - area, 12–13
 - covering materials
 - flexible types, 13–14
 - rigid types, 13
 - coverings, 118–119
 - poly films, 120–121
 - polycarbonate panels, 123–124
 - screenhouses, 14–15
- Ground anchors, 110–111
- Growers, 103
- H**
- Hall, Bernarr J., 2
- Hanging baskets, 134–135, 135*f*
- HDPE. *See* High-density polyethylene (HDPE)
- Heat retention curtains, 124
- Heater bands, 31
- High tunnels, 6–7, 107
 - cucurbits, 114
 - movable high tunnels, 110–111
 - North America regions, 113–114
 - orientation, 109
 - plasticulture technology, 116
 - structures, 108*f*, 110*f*
 - temperature management, 111
 - Temperature profile for stationary, 112*f*
 - water, 112
 - yield and total revenue, 115*t*
- High-density polyethylene (HDPE), 3, 24–25, 138, 187, 190
- Home compostable pots, 141
- Hoop house, 119–120
- Hoop-supported row covers, 72–73
- Horizontal silos, 150–151
 - oxygen barrier films for, 167–171
 - bunker and clamp silo
 - comparison, 170*f*
 - plastic films for, 155–158, 157*f*
 - covering typology, 160*t*
 - maximum solar radiation, 159*f*
- Horticultural farms, 149
- Horticulture plastics, 129
 - bioplastic, 140–141
 - container standards, 133–135
 - container-grown plants, 129–131, 130*f*
 - eco-friendly growing containers, 139–140
 - modern plastic growing container, 132–133
 - nursery containers, 135–137
 - reusable and recycling, 138–139
- Hydrocarbons, 190–192
- Hydroponics, plastics in, 126–127
- I**
- Indeterminate cultivars, 113–114
- Industry Guide to Marketing Container Plants, 133
- Infrared-transmitting mulches, 49
- Injection
 - injecting fertilizers, 101–102
 - injection-molded pots, 132–133
 - molding method, 133–134
 - and safety equipment, 91–92
 - systems, 101–102
- Inline emitters, 88–90, 90*f*
- Insect
 - exclusion, 62
 - pests, 66–68
- Insecticide-treated nets, 68
- Integrated Packaging Group (IPG), 153–154
- Integrated pest management, 16–18
- Intensive cropping, 54
- “Intensive” vegetable production system, 45
- Intercropping process, 113
- Iowa State University, 140

IPG. *See* Integrated Packaging Group (IPG)

Irrigation, 15
 controllers, 99

L

L. esculentum. *See* Tomatoes (*L. esculentum*)

Lactobacillus buchneri, 155–156

Land Grant Institutions, 45

Landfilling plastic, 193

Lay-flat, 40, 85–88

LDPE. *See* Low-density polyethylene (LDPE)

Leafy greens, 113

Leafy greens, 114

Light, 64

Light diffusing polycarbonate, 123–124

Linear low-density polyethylene (L-LDPE), 3, 9–10

Linear-type polymers, 24–25

Livestock farms, polymers and plastic types on, 145–150

L-LDPE. *See* Linear low-density polyethylene (L-LDPE)

Low tunnels, 6–7, 10, 61, 72, 72*f*

Low-density polyethylene (LDPE), 3, 9–10, 13, 15, 24–25, 46, 145–146, 157, 187, 190
 films, 11, 154–155

Lower-molecular-weight components, 23

M

Mater-Bi (MB). *See* Starch-based polymer

Mechanical forming method, 133–134

Mediterranean

 basin, 11

 diets, 2

 greenhouse agrosystem, 12

 region, 11

Melons, 114

Microclimate, 107, 114

Microirrigation, 79–80, 107–108

Modern hydroponic production systems, 117–118

Modern plastic growing container, 132–133

 hanging baskets, 135*f*

 transplant machines, 134*f*

Moist animal feeds, 165

Molecular weight distribution, 23

Molten polymer, 29, 36, 38–39

Molten tube, 37–38

Monoaxial orientation, 36

Movable high tunnels, 110–111

Mulches, 9–10

Multiwall polycarbonate panels, 123–124

N

National Agricultural Plastics Association (NAPA), 1

National Greenhouse Manufacturers Association (NGMA), 118–119

Near-infrared spectroscopy optical separators, 189–190

NFT. *See* Nutrient Film Technique (NFT)

NGMA. *See* National Greenhouse Manufacturers Association (NGMA)

Nip rolls, 40

Nitrogen, 102

Nonsupported row covers, 72–73

Nonwoven materials, 62

North America

 European crop diversification programs, 3

 Extension Educators, 2

 plastic materials, 3

 plastics in agriculture, 1

 plasticulture, 1

- Northern greenhouses, 124
 Nursery containers, 135–137
 air-pruning pots growing system, 136–137
 pot-in-pot growing system, 136, 136*f*
 Nutrient Film Technique (NFT), 117–118
 Nutrients, 101–102
- O**
 OB films. *See* Oxygen barrier film (OB films)
 OM. *See* Organic matter (OM)
 Online emitters, 88–90, 90*f*
 Organic matter (OM), 155–156
 Orientation, 26–27
 Overwintering, 70–73
 blackberry, 70–71
 container-grown nursery stock, 73
 strawberry, 70
 vegetables, 72–73
 winter vegetable production, 71
 Oxygen
 diffusion, 156–157
 impermeability, 172
 infiltration, 156–157
 Oxygen barrier film (OB films), 154–155, 167–168
 for horizontal silos, 167–171, 169*t*
 new perspectives of bioplastics on livestock farms, 174–176
 for silage conservation, 165–176, 166*t*
 stretch films for wrapped bales, 171–174
- P**
 PAR. *See* Photosynthetic-active radiation (PAR)
 PAs. *See* Polyamides (PAs)
 PC. *See* Polycarbonate (PC)
 PE. *See* Polyethylene (PE)
Peponapis pruinosa. *See* Squash bee (*Peponapis pruinosa*)
 Perforated clay pipes, 80–81
 Perforated metal pipes, 80–81
 Perforated polyethylene, 62
 Petro-based polymers, 140
 PHA. *See* Polyhydroxyalkanoates (PHA)
 Photodegradable mulch films, 10
 Photodegradable plastic, 149–150
 Photodegradable plastic mulch, 55
 Photosensitive plastic films, 14
 Photosynthetic photon flux density (PPFD), 64
 Photosynthetic-active radiation (PAR), 10
 PLA. *See* Polylactic acid (PLA)
 Plant
 debris, 16
 physiological processes, 111
 plant-based bioplastics, 175
 Plastic films, 3, 21. *See also* Plastic mulches
 for animal feed storage, 150–165
 feed conservation applications, 164–165
 plastic development for silage conservation, 151–155, 152*t*
 plastic films for horizontal silos, 155–158, 157*f*
 stretch films for wrapped bales, 158–164
 extrusion, 28–41
 polymer properties, 22–28
 processing parameters, 41–43
 Plastic mulches, 5, 45–46. *See also* Plastic films
 advantages
 cleaner product, 53
 double/triple crop, 54
 earlier and higher overall yields, 52
 fewer weed problems, 52
 fumigation and soil solarization, 53
 gas exchange, 53

- Plastic mulches (*Continued*)
- reduced drowning of crops, 54
 - reduced evaporation, 52
 - reduced fertilizer leaching, 52
 - reduced soil compaction, 53
 - root pruning elimination, 53
 - color, 47–51
 - disadvantages
 - initial cost, 56
 - removal and disposal, 54–56
 - PE, 45
 - specifications, 47
- Plastic(s), 54, 117–118, 129, 187, 190
- in animal production, 8
 - bunker silo covers, 150–151
 - coverings, 118–119
 - greenhouses, 7
 - coverings, 118–124
 - hanging baskets, 134–135
 - in hydroponics, 126–127
 - mulching, 149–150
 - plastic-covered greenhouses, 2, 11–12
 - plastic-molded emitters, 81–82
 - polymers, 187
 - pots, 131, 133*f*
 - trays, and flats, 124–126
 - types on livestock farms, 145–150
 - distribution of plastic, 148*f*
 - plastic purchasing, 147*f*
 - plastic utilization, 149*t*
 - uses in agriculture, 15
- Plasticizers, 151
- Plasticulture, 1
- in Europe, 8
 - technology, 116
- Plastofuel, 138–139
- Plugs trays, 134
- PMMA. *See* Polymethacrylate (PMMA)
- Point-of-purchase (POP), 132
- Poly films, 120–121
- Poly-3-hydroxybutrat, 140–141
- Poly-lock systems, 119–120
- Polyamides (PAs), 150–151, 165–166
- Polycarbonate (PC), 12, 22–23
- greenhouse panels, 123–124
 - sheets, 118–119
- Polyester, 62, 118–119
- heat retention curtains, 124
- Polyethylene (PE), 1–5, 13, 22–23, 45–46, 72, 189
- films, 145
 - layer, 107
 - plastic, 107
 - covering, 107–108
 - sheets, 62
 - terephthalate glycol, 118–119
 - tubing, 79–82
- Polyhydroxyalkanoates (PHA), 140–141
- Polylactic acid (PLA), 140
- Polymerization, 23, 26
- Polymers, 145
- chain, 23–24
 - and products on livestock farms, 145–146, 146*t*
 - properties, 22–28
 - “cold flow”, 27–28
 - melt indexes, 23
 - molecular weight distribution, 23
 - orientation, 26–27
 - polymer chain, 23–24
 - thermoplastic materials, 25
- Polymethacrylate (PMMA), 12–13
- Polypropylene (PP), 1, 6, 62, 70, 138, 145–146, 187, 189–190
- trays, 138
- Polystyrene (PS), 22–23, 138, 187, 190
- Polyurethane, 15
- Polyvinyl chloride (PVC), 3, 118–119, 151
- Polyvinyl fluoride, 118–119
- POP. *See* Point-of-purchase (POP)
- “Pot-bound” roots, 136–137

- Pot-in-pot growing system, 136, 136*f*
 PP. *See* Polypropylene (PP)
 PPFD. *See* Photosynthetic photon flux density (PPFD)
 Primary recycling process, 188
 Profile extrusion, 29
 Protected cultivation, 9
 Proteknet, 62
 PS. *See* Polystyrene (PS)
 Punch plastic system, 149–150
 PVC. *See* Polyvinyl chloride (PVC)
 Pyrolysis, 191–192
- Q**
 Quaternary recycling process, 188
 Quonset structures, 111
 Quonset style, 119–120
- R**
 Rain gutters, 112
 Recyclable, 139
 Recycling, 188–190
 contaminant specifications, 189*t*
 plastic trays, 138–139
 Reduced drowning of crops, 54
 Reduced soil compaction, 53
 Reflective mulches, 52
 Reinforced fiberglass, 13
 Relative humidity (RH), 64–65, 162
 Residues, 16
 Reusable trays, 138–139
 Reuse of agricultural plastics, 193–194
 Reusing tubing or tape, 103
 RH. *See* Relative humidity (RH)
 Rigid
 molded plastics, 8
 Rigid, 193–194
 types, 13
 Root
 crop, 114
 pruning elimination, 53
 root-regulating copper hydroxide compound, 137
- Row covers, 6, 10–11, 61
 Brussels sprouts, 63*f*
 on crop microclimate, 63–65
 airflow, 65
 light, 64
 relative humidity, 64–65
 temperature, 63–64
 vapor pressure deficit, 64–65
 on crops
 beneficial insect populations, 68–69
 crop quality, 69
 insect pests, 66–68
 overwintering, 70–73
 season extension and yield increases, 65–66
 fall harvest of high-quality kale leaves, 67*f*
 installed over mixed vegetables, 66*f*
 materials, 62–63
 technologies, 61
- S**
 Screenhouses, 14–15
 Season extension and yield increases, 65–66
 Secondary recycling process, 188
 Semicrystalline materials, 25, 40
 Sequential process, 36–37
 Silage bags, 150–151
 Silage conservation
 innovative oxygen barrier films for, 165–176
 plastic development for, 151–155, 152*t*
 “Silawrap”, 153–154
 Silo, 150–151, 156–157
 Simultaneous stretching process, 37
 Slitted polyethylene, 62
 “Slot casting” method, 46
 “Snaking”, 82–83
 Soil, 53
 erosion, 84
 moisture, 80–81
 sensors, 99–100

Soil (*Continued*)

- mulching, 9–10
- solarization, 53
- temperature, 48, 63–64
- texture, 93–94
- water-holding capacity and available water, 93–94

Solanum species, 114

Spaghetti

- analogy, 26
- noodle analogy, 26
- “Spaghetti”-type tubing, 85–88
- tubing, 81–82

Specialty crops, 107–108

Spin-Out, 137

Sprinkler irrigation, 83–85

Spunbonded materials, 62

Squash bee (*Peponapis pruinosa*), 68–69

Stalk, 38–39

Starch-based polymer, 175

Static hydroponic systems, 112–113

Straw mulch, 70

Strawberries, 70, 114–116

Stretch films for wrapped bales, 158–164, 163f

Stretch-wrap silage production, 161–162

Subirrigation, 83–85

Subsurface drip irrigation, 82–83

Subsurface drip systems, 82–83

Summer squash (*Cucurbita pepo*), 114

Summit Plastic Company, 140

Surface drip irrigation, 82–83

Surfactant, 120–121

Sustainability, 132, 140

Synthetic agrotexile fabrics, 62

T

Tedlar film, 122

Temperature, 25, 27, 63–64

- in barrel, 31
- management, 111

Tenter frame line, 36–37

Tenterhooks, 36–37, 43

Tertiary recycling process, 188, 191

Thermoformed containers, 132–133

Thermoplastics, 22

- materials, 16, 25

Thermosets, 22

Thinner-walled tubing, 81–82

Tomatoes (*L. esculentum*), 113–114

Trial-and-error process, 29

Tubing placement in row, 90–91

Tunnels, high/low, 6–7

U

Ultraviolet (UV), 46, 151

- inhibitors, 120–121
- rays, 13

Uniformity, 99

U.S. Department of Agriculture (USDA), 70–71, 107

V

Vacuum containers, 132–133

Vapor pressure deficit, 64–65

Vegetable crops, 101–102

- production, 45

Vegetable Production and Entomology, 2

Vegetables, overwintering, 72–73

Velocity difference, 32–33

Venturi-type

- injection system, 101–102, 101f
- injector, 92

Vinyl alcohol copolymer (EVOH), 166–167

- EVOH-coextruded barrier films, 166–167

W

Warm microclimate, 113–114

Warm-season crops, 113–114

Water, 79–81, 83–84, 108–109

- application uniformity, 99
- efficiency, 84
- water-holding capacity, 93–94

- Wavelength-selective mulches, 49, 52
Wax, 22
Weeds, 52
 problems, 84
White plastic, 120–121
White-on-black mulches, 52
Winter protection, 70, 72–73
Winter vegetable production, 71
Wondermesh, 62
Woven mesh net, 62
Woven polyethylene net materials,
 67
- Wrapped bales
 oxygen barrier stretch films for,
 171–174, 173*t*
 stretch films for, 158–164, 163*f*
 characteristics of stretch films,
 173*t*
 DM losses, 173*f*
 surface covered by mold, 174*f*
- Y**
Yeasts, 156–157